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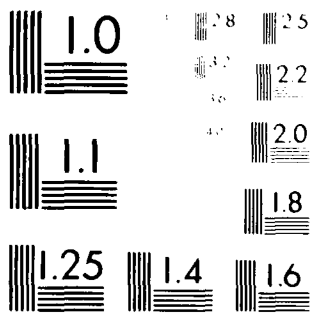

MICROCOPY RESOLUTION TEST CHART

MEMORANDUM REPORT ARBRL-MR-02995

SENSITIVITY ANALYSIS OF THE PKHDOC COMPONENT VULNERABILITY METHODOLOGY

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February 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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This study was conducted to investigate and quantify the sensitivity of PKH's (component probabilities of kill given a hit) produced by the Ballistic Research Laboratory's component vulnerability program, PKHDOC, to attack direction and to variations in several program inputs. Included in this study is a comparison of PKH's for individual faces of a component with the "average component PKH's" produced by PKHDOC. Also analyzed are the effects on component PKH of variations in fragment shape factor, kill hole requirement, component material thickness, and component sensitive area.

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I. OBJECTIVE

The objective of this study is to investigate and quantify the sensitivity of component PKH's (probabilities of kill given a hit) to attack direction and variation in several inputs of the PKHDOC component vulnerability model, and to determine which elements in the model require detailed, accurate representation.

II. BACKGROUND

One of the necessary inputs for a detailed "point-burst" methodology* for analytically estimating the vulnerability of a target is a method for predicting the probability of rendering a component nonfunctional ("killing" the component), given that it is subjected to some damage mechanism.

The most satisfying method, and potentially the most accurate one, of developing these conditional kill probabilities (PKH's) for components is by experiment. Unfortunately, this is not possible because of the tremendous expense in terms of quantity of components required, manpower, financial resources, and, perhaps most of all, the time required.

Realizing these constraints, a number of years ago the Ballistic Research Laboratory (BRL) developed an analytical method of estimating component PKH's. The method relies heavily on the component evaluator's engineering background and experience based on field tests in which fragments were fired against targets similar in design and material to the components to be analyzed. Also, the method involves predicting the residual mass and velocity of an impacting fragment after it has perforated a plate of known material. The evaluator must know how a component performs its function and how it can be rendered nonfunctional.

Presently, impacting fragments are considered to be the source of killing damage. The damage ascribed to each component when struck by a single fragment is considered to be a function of the fragment's shape, mass, and speed at impact, all of which are assumed to be known from prior computations based upon terminal ballistics submodels.

A vulnerability analysis of a target of interest, e.g., the M48A1 Tank, is begun by identifying the essential target systems and considering the components which form each system. Those components whose functions are necessary to the continued operation of any of the essential target systems are termed critical components.

Detailed information about the critical components is obtained by the component evaluator if it is available. (When detailed information is not available, the evaluator must rely on best estimates, his experience, and his engineering judgments). This information includes the six faces of a component which are obtained by projection of the component onto the six faces of an enclosing box (Figure 1). This allows the three-dimensional component to be represented by a set of six two-dimensional faces. (Currently, the PKH model treats all components as having six faces, with each basic face subjected to attack from 0^{o} and from 45^{o} obliquities only). Generally, the entire presented area of a

* Sometimes referred to as "component level methodology."

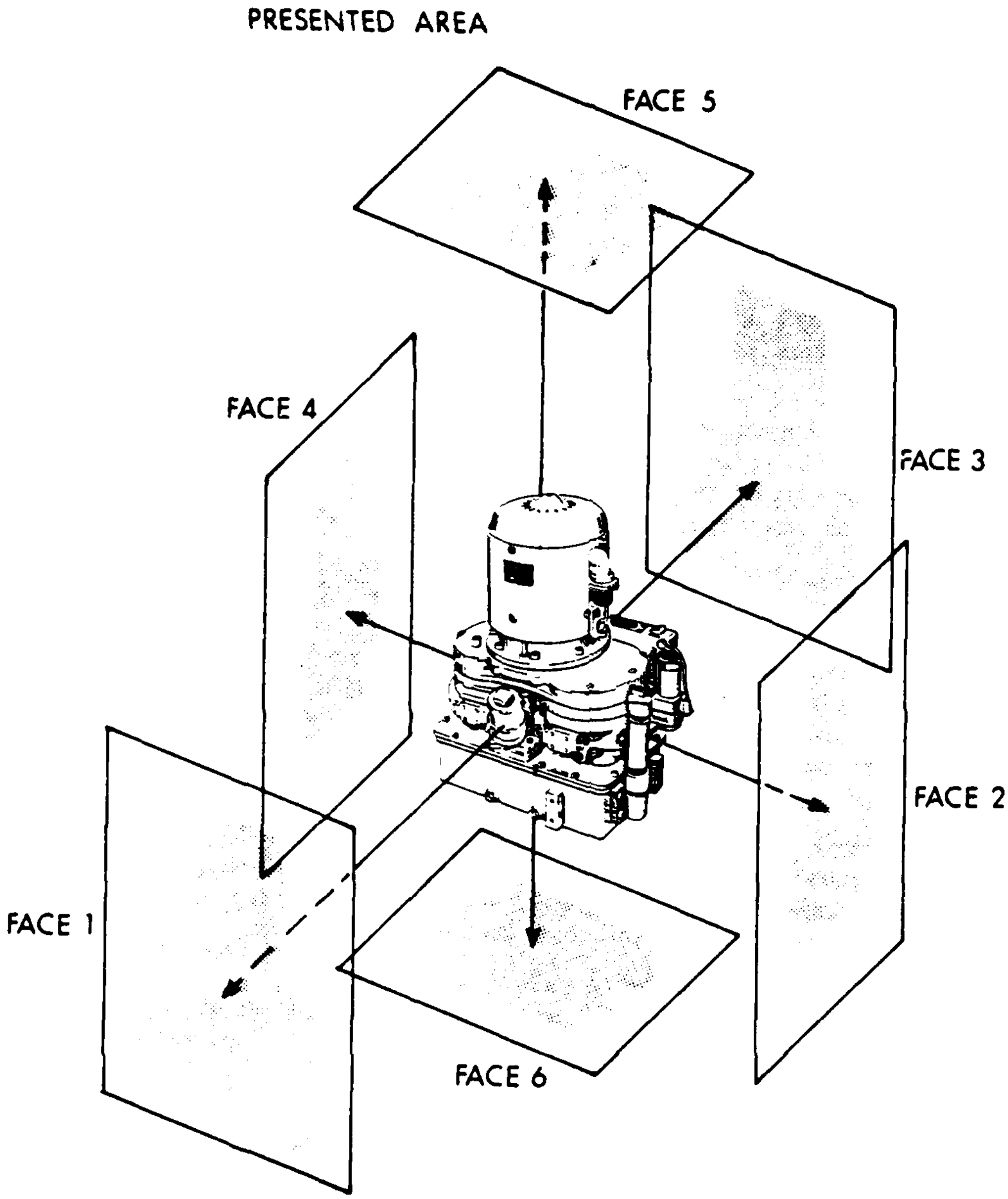

Figure 1. Basic Component Faces

component is not susceptible to killing damage by the mechanism being considered; that part which is susceptible is defined as the sensitive area. The kill requirement for a component is then defined in terms of a minimum hole size in the sensitive area that will kill the component. (The evaluator, in predicting this minimum hole, draws upon his background and experience to estimate the fracture, breaking, lodging, electrical shorting, shock, or whatever effect he believes would have resulted from the impact of the predicted fragment). Between the outer surface of the component and the sensitive area within, a number of functionally inert barriers may exist. These barriers are taken into account by specifying their thickness and material composition.

The PKH for a critical component is defined as the probability of rendering the component nonfunctional given it is subjected to some damage mechanism. The PKHDOC Computer Program provides a method for computing the PKH's for the various critical components of a target. The methodology employed in this program is applicable to attacks by penetrators such as fragments, bullets, or flechettes; it is not directly applicable to damage mechanisms such as blast, shock, or flame.

The program considers fragment penetrators of selected masses, impacting at velocities between a specified minimum and maximum at intervals of 100 feet per second. Using the THOR[1] penetration equations and the input data for the component which identifies the barriers to be penetrated before the sensitive area of the component is entered, the program computes the residual mass and velocity of the fragment after each barrier is penetrated. This computation continues until the fragment is defeated or the sensitive area is penetrated.

Upon penetration of the sensitive area, the size of the hole made by the fragment is computed, and a determination is made as to whether or not the component has been rendered nonfunctional.

The PKH for each fragment mass and velocity is computed as the ratio of the amount of sensitive area killed by these fragments to the total presented area of the component. (The computed PKH is a weighted average over all expected attack directions. This results in a single PKH for the component which is independent of attack direction.)

In this manner, the PKH for each fragment mass and velocity combination is computed, and these results are presented in tables. However, the primary result is a pair of functions (GENREG and MAXFIT regression curve fits to the computed tables) which are used together to compute the PKH given the mass and velocity of the impacting fragment.

For a more comprehensive discussion of the PKHDOC methodology, the reader is referred to "Documentation of $P_{K/H}$ Computer Program."[2]

[1] *Resistance of Various Metallic Materials to Perforation by Steel Fragments* ; *Empirical Relationships for Fragment Residual Velocity and Residual Weight* (U), Project THOR Technical Report No. 47, Institute for Cooperative Research, Ballistic Analysis Laboratory, Johns Hopkins University, Baltimore, MD, April 1961.

[2] Armament Systems, Inc., *Documentation of $P_{K/H}$ Computer Program* , Anaheim, CA, November 1974.

III. APPROACH

The PKHDOC program currently (August 1978) in use by the BRL for assessing the vulnerability of armored vehicle components was modified to allow changes to be made easily to component kill requirements (hole diameters), sensitive areas, and material thicknesses. In addition, modifications were made to allow for computing PKH's for individual component faces and to provide additional PKH output from the present curve fitting routines.

Initial sensitivity studies were conducted on a single M48A1 Tank component which was considered to be critical to the mobility function of the tank. This component was of a nonhomogeneous, nonsymmetrical type and consisted of several faces which differed in material type, material thickness, number of barriers, and presented and sensitive areas. The modified PKHDOC program was then exercised for the selected component to obtain output data on the following:

A. *Sensitivity to Attack Direction*

How do the PKH's vary between the individual component faces? How do these PKH's compare with both the "average" component PKH and the PKH derived from the curve fitting routines currently in use?

B. *Sensitivity to Fragment Shape Factor*

How do the computed PKH's vary when the shape factor of the impacting spall fragment is changed?

C. *Sensitivity to Engineering Judgments*

How do the PKH's change with variations in the kill criterion (hole diameter), sensitive area, and material thickness? How do these PKH variations compare with the "average" component PKH's and the PKH's derived from the curve fitting routines currently in use?

IV. SENSITIVITY TO ATTACK DIRECTION

A. *Method*

An M48A1 Tank Engine/Transmission Oil Cooler was selected as a test component representative of a nonhomogeneous, nonsymmetrical type component with differences among several faces in material type, number of barriers, material thickness, sensitive and presented areas, and hole diameter required to kill the component. This component was considered by the evaluator to be "critical" to the tank's mobility function since its loss would result in a complete loss of tank mobility (Mobility Kill) due to transmission and/or engine failure from oil starvation. The input data for this component are listed in Table 1.*

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* The PKHDOC program is written to accept inputs in English units, and the resulting PKH's are tabulated for velocity steps in multiples of 100 ft/sec. As a result, this report will express inputs and results in English units with occasional parenthetical reference to equivalent metric units.

The selection of fragment masses and velocities was based on available representative data for behind-armor debris (spall) for shaped charge and kinetic energy penetrators. The mass/velocity ranges selected were believed to include about 90% of the expected combinations present in the spall distribution. The maximum velocity selected was 5000 ft/sec (1524 m/s). The selected spall masses are listed in Table 2. This narrow mass range was also selected in order to minimize step increments to get a better feel for PKH changes due to input variations, (e.g., shape factor, hole size) and to reduce the range over which the curve fit routines are utilized (to reduce curve fit errors).

TABLE 1. Component Data for Engine/Transmission Oil Cooler, M48A1 Tank

Face	Kill Hole Diameter (inches)	Number of Barriers	Barrier 1 Material Type/ Thickness (inches)	Barrier 2 Material Type/ Thickness (inches)	Presented/ Sensitive Area(sq inches)
1	0.09	1	7/0.01		265.7/247.4
2	0.09	2	1/0.10	7/0.01	419.1/134.8
2	0.20	2	1/0.10	7/0.01	419.1/269.6
3	0.20	1	7/0.01		265.7/247.4
4	0.09	2	1/0.10	7/0.01	419.1/134.8
4	0.20	2	1/0.10	7/0.01	419.1/269.6
5	0.09	1	1/0.10		150.0/46.6
5	0.20	1	1/0.10		150.0/93.2
6	0.09	1	1/0.10		150.0/46.6
6	0.20	1	1/0.10		150.0/93.2

Material type 1 = mild steel
Material type 7 = copper

TABLE 2. Fragment Masses Selected as PKHDOC Input

Fragment Mass (grains)	Fragment Mass (grams)	Fragment Mass (grains)	Fragment Mass (grams)
0.01	0.001	8.0	0.52
0.05	0.003	10.0	0.65
0.10	0.006	12.0	0.78
0.50	0.03	14.0	0.91
1.00	0.06	16.0	1.04
2.00	0.13	18.0	1.17
3.00	0.19	20.0	1.30
4.00	0.26	40.0	2.59
5.00	0.32	60.0	3.89
6.00	0.39	80.0	5.18

The PKHDOC program was exercised and the average PKH's computed for the component (weighted average PKH over all six component faces). The program was next used to compute the PKH for each face of the component and the results compared with the average PKH's and with PKH's from the GENREG/MAXFIT curves. In the PKHDOC program, the GENREG and MAXFIT regression curve coefficients are generated for use in the point-burst model to predict component PKH for any mass/velocity combination. GENREG provides a curve which gives component PKH as a function of fragment momentum per average presented area of the fragment. This curve is obtained by a regression fit of fragment MV/A (M = mass, V = velocity, A = average presented area) to PKH for all cases in which the computed PKH's are non-zero. MAXFIT produces a curve which gives the maximum component PKH attainable for *any* fragment mass and is used to limit the GENREG PKH values. One GENREG and one MAXFIT curve is produced by PKHDOC for each component, and these two curves are utilized in the point-burst model to produce the component PKH as a function of striking fragment mass and velocity. The component PKH is the minimum PKH of the two curves ("GENREG/MAXFIT Curve Combination"). In this study the GENREG and MAXFIT curves (one set of coefficients for each curve) were obtained for the mass/velocity range specified above. Then a *specific* mass was selected, and a PKH curve plotted (derived curve) as a function of velocity from the results of the GENREG/MAXFIT curve combination. This resulting "derived curve" will be referred to as "curve."

PKH's were computed for the commonly used random artillery, fragment shape factor, .0145, and the spherical fragment shape factor, .0077 (inches^2/grains$^{2/3}$). Both shape factors are for steel fragments.

B. *Results*

The results are presented in Figure 2. In Figure 2(a-q) PKH is plotted as a function of velocity for specific fragment masses ranging from 0.5 to 80.0 grains. PKH's for individual faces are identified by the face number. The PKH averaged over all faces (independent of attack direction) is identified as "AVE." The PKH derived from the GENREG/MAXFIT curve combination is identified as "CURVE." This "curve" shows how well the GENREG/MAXFIT curve combination (which covers PKH for *all* masses) represents the PKH's for the specific mass selected. The results in Figure 2 are only for the .0145 shape factor; a comparison of shape factor results will be presented later.

In Figure 2f it will be noted that for a fragment with a mass of 5.0 grains with a velocity of 500 ft/sec the computed average PKH (AVE) is .30 and the PKH from the curve fit (curve) is 0.0. In fact the component has four faces which are not vulnerable to this fragment mass/velocity combination and two faces which have a PKH of over .90. For a 14.0-grain fragment (Figure 2k) with a velocity of 3900 ft/sec, the average PKH (AVE) and curve fit PKH (CURVE) are in good agreement (≈.48). However, this mass/velocity combination has a computed PKH of .94 for two faces and only .25 for the four other faces. Similar face-to-face PKH variations can be seen throughout the data in Figure 2.

These results indicate that for this component it is very important to consider the attack direction since the PKH varies considerably between component faces. If it was determined that 95% of the spall fragments from a given shaped charge had masses of 3.0 grains or less, then it will be noted (Figure 2a-d) that this component would never have a PKH greater than .32 from the curve fit. However, one face of the component actually has a PKH of over .92 for most of the mass/velocity combinations from 0.5 to 3.0 grains. If this component's vulnerable face were positioned in the tank such that it was impossible for spall to hit it, e.g., against the engine block, then the curve fit PKH would be acceptable *(due to chance?)*. On the other hand, if that face were oriented such that it could be easily struck by spall, then consideration of the PKH's for each individual face would provide a more realistic and accurate vulnerability prediction. This component's sensitivity to attack direction is also important when it comes to vulnerability reduction. The face of the component which must be spall shielded/hardened or reoriented to increase survivability could be accurately determined.

As seen in Figure 2, the "CURVES" do not fit the "AVE" computed PKH's very well, indicating that for this component fragment MV/A does not correlate well with component PKH. Figures 3 and 4 are plots of the GENREG and MAXFIT curves for this component for fragment shape factor .0145. In these figures the "X" represents a data point (calculated from the tabulated PKH data) and the "*" represents a point on the regression curve fit to the X's. The scatter in the data shown in Figure 3 indicates that fragment MV/A does not well represent component PKH. (NOTE: Some of the X's represent multiple data points which appear as one point on the plot). In Figure 4 it will be noted that the MAXFIT curve prevents the PKH from reaching 1.0 even though several data points predict a PKH of 1.0.

Fig. 2(a) - 0.5 Grain

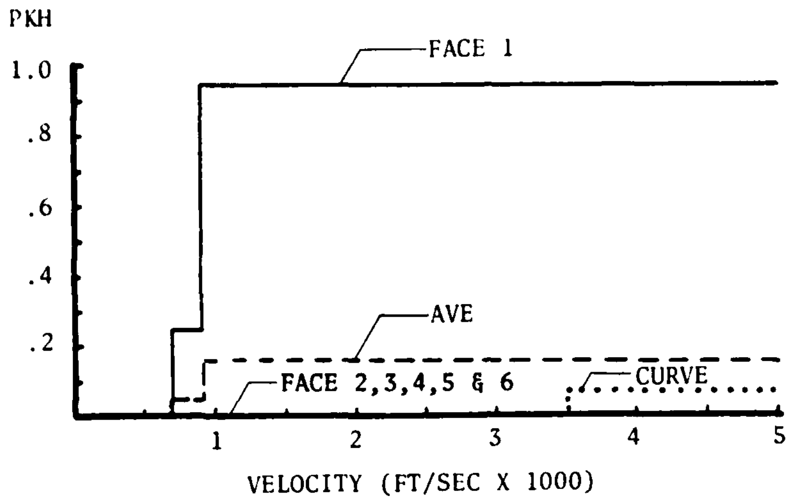

Fig. 2(b) - 1.0 Grain

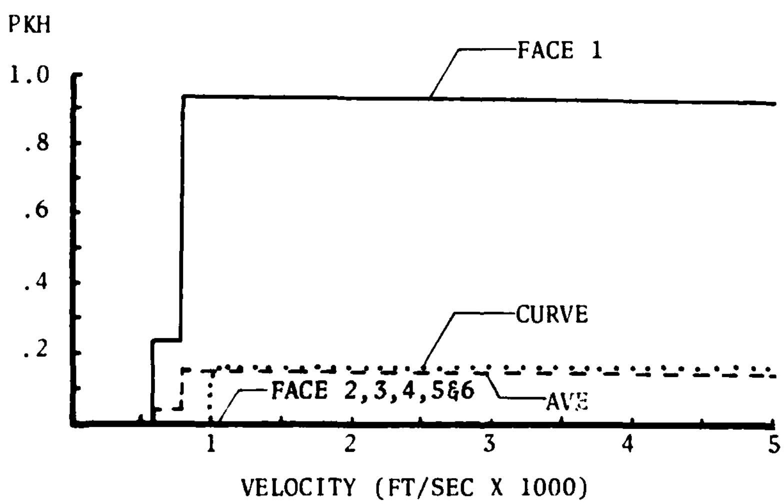

Figure 2. Probability of Kill (Given a Hit) as a Function of Velocity for Given Fragment Masses for the M48A1 Tank Engine/Transmission Oil Cooler

Fig. 2(c) - 2.0 Grains

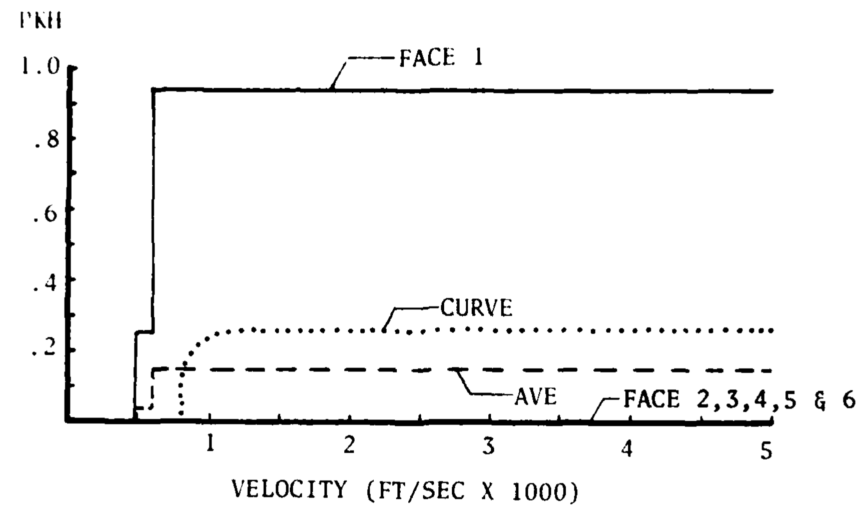

Fig. 2(d) - 3.0 Grains

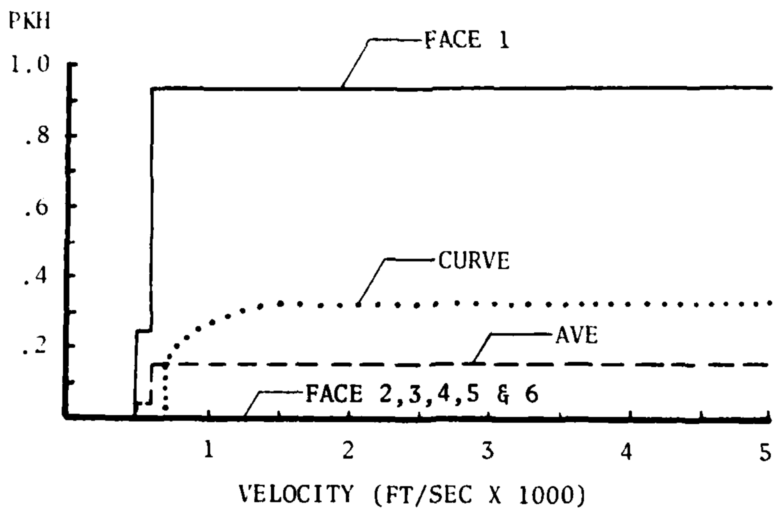

Figure 2. (Continued)

Fig. 2(e) - 4.0 Grains

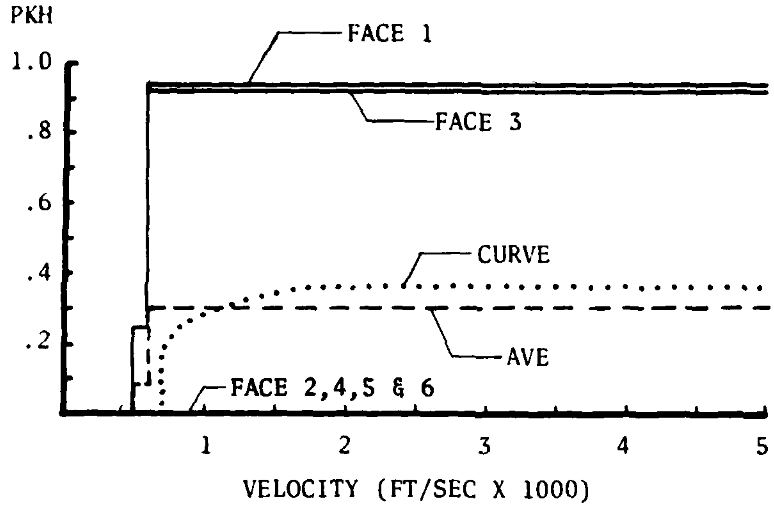

Fig. 2(f) - 5.0 Grains

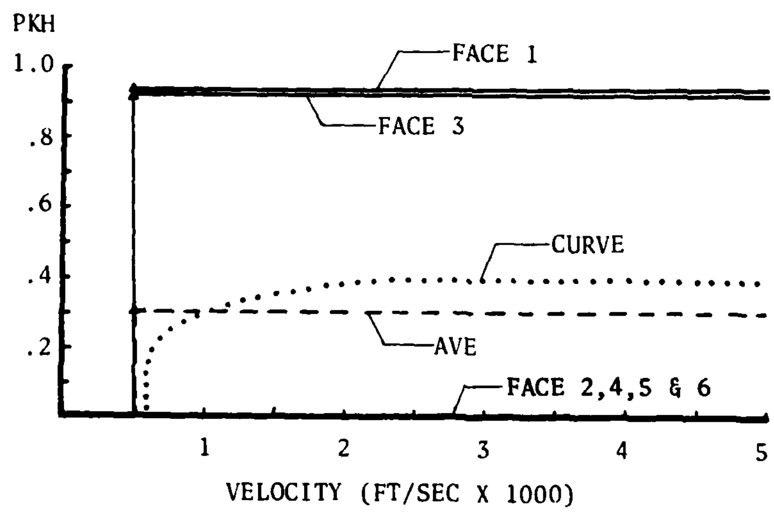

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Figure 2. (Continued)

Fig. 2(g) - 6.0 Grains

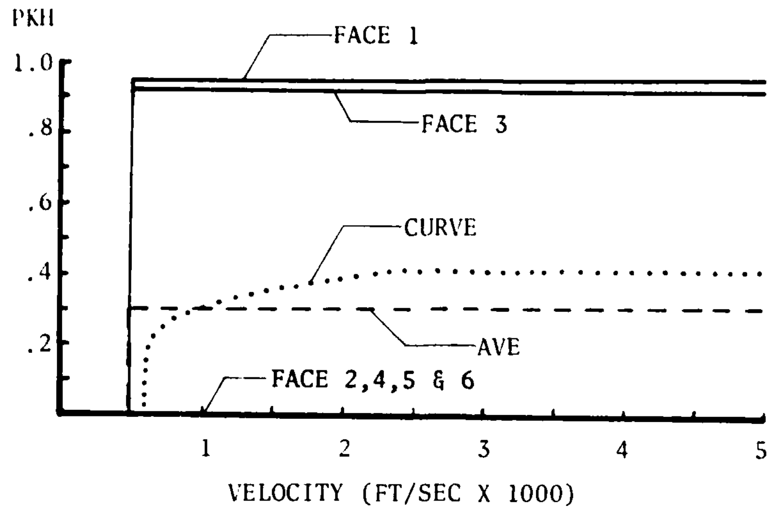

Fig. 2(h) - 8.0 Grains

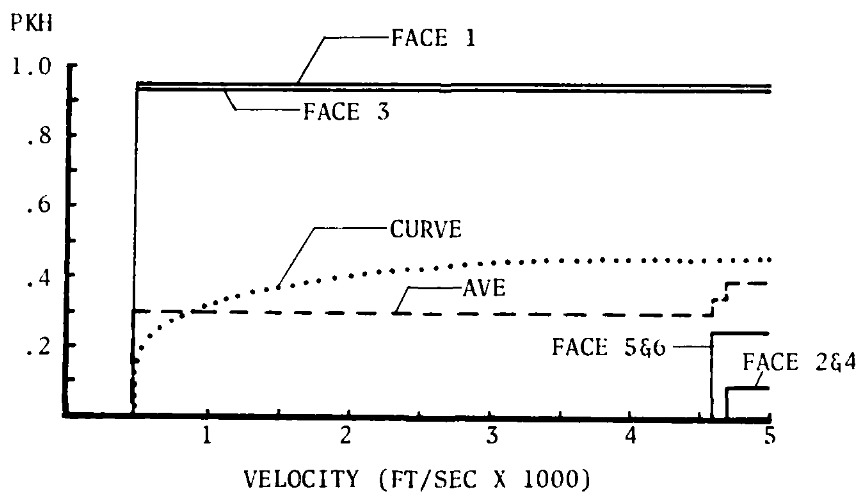

Figure 2. (Continued)

Fig 2(i) - 10.0 Grains

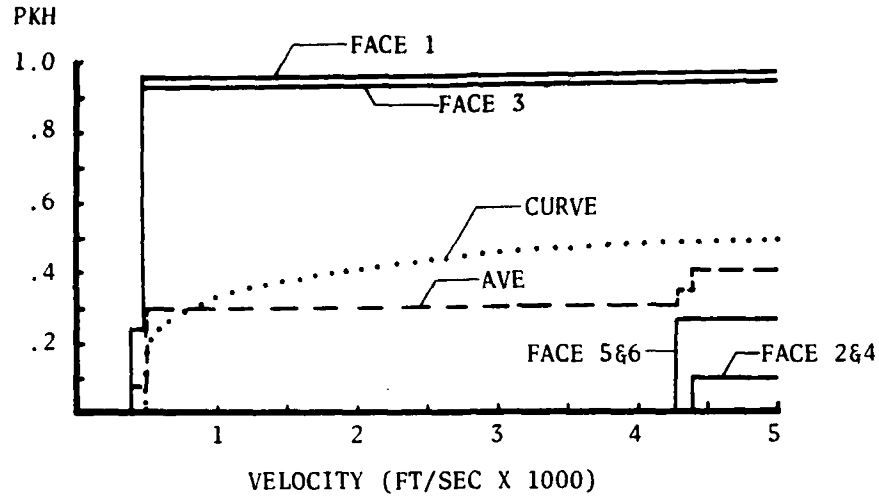

Fig 2(j) - 12.0 Grains

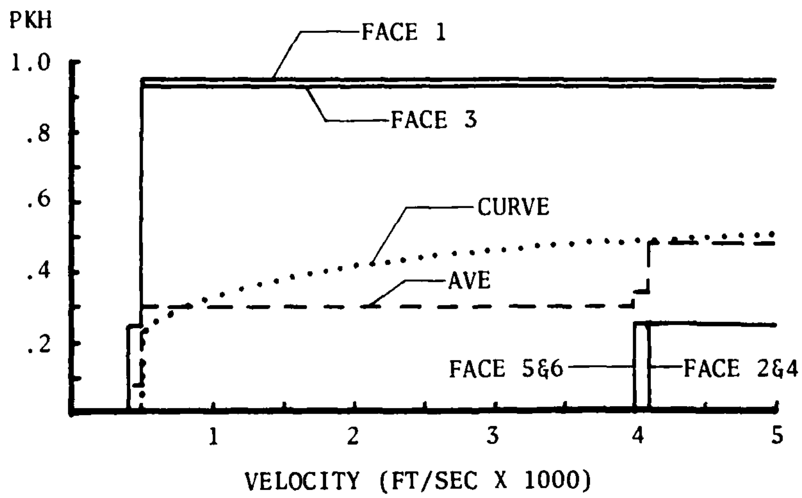

Figure 2. (Continued)

Fig. 2(k) - 14.0 Grains

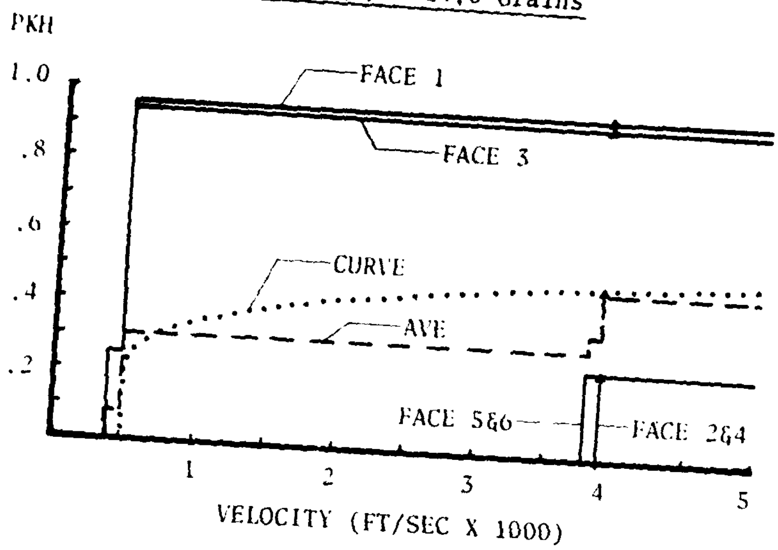

Fig. 2(l) - 16.0 Grains

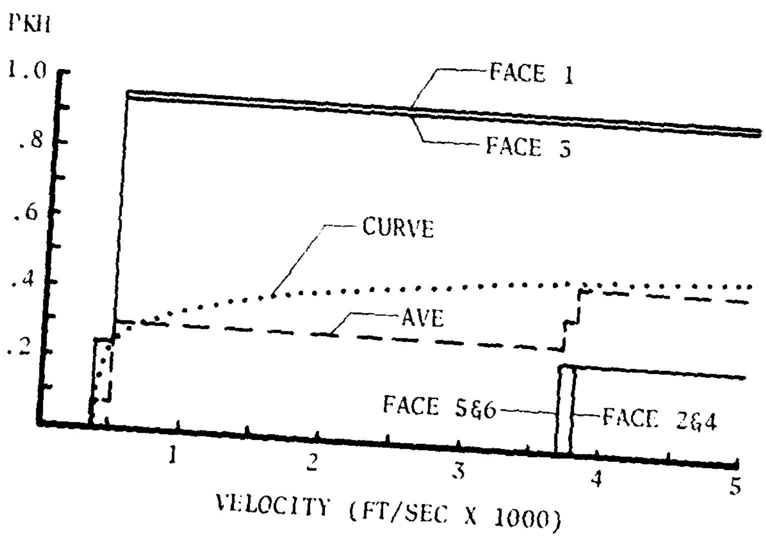

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Figure 2. (Continued)

Fig. 2(m) - 18.0 Grains

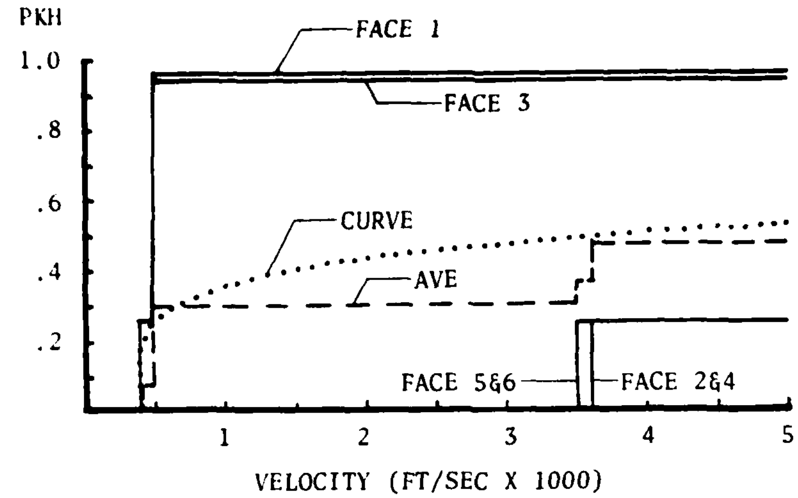


Fig. 2(n) - 20.0 Grains

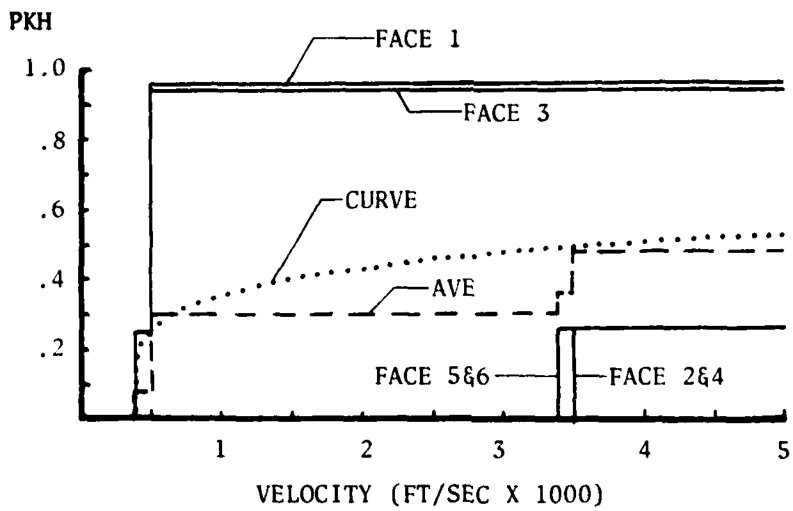


Figure 2. (Continued)

Fig. 2(o) - 40.0 Grains

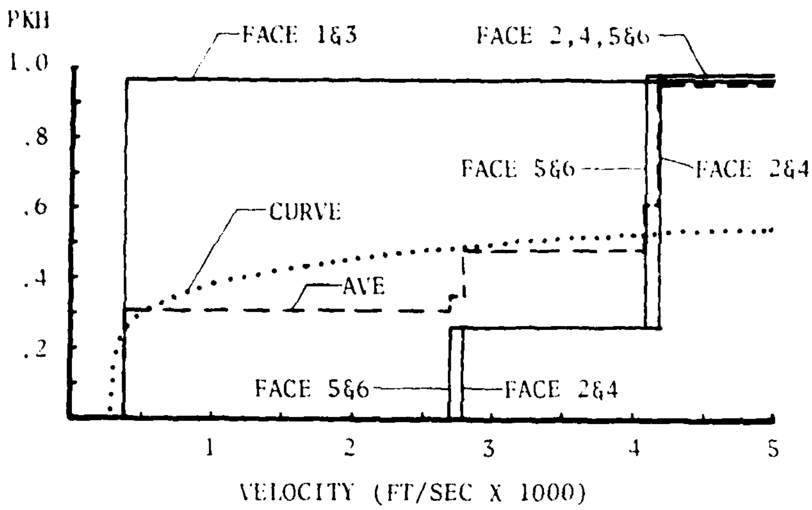


Fig. 2(p) - 60.0 Grains

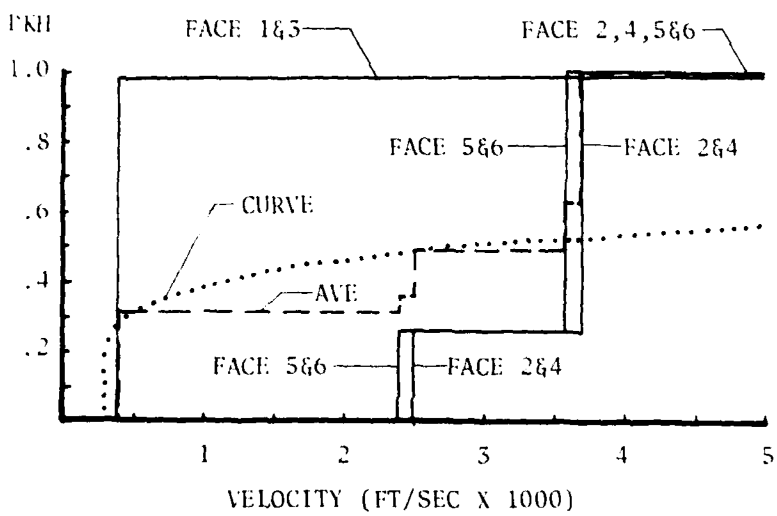


Figure 2. (Continued)

Fig. 2(q) - 80.0 Grains

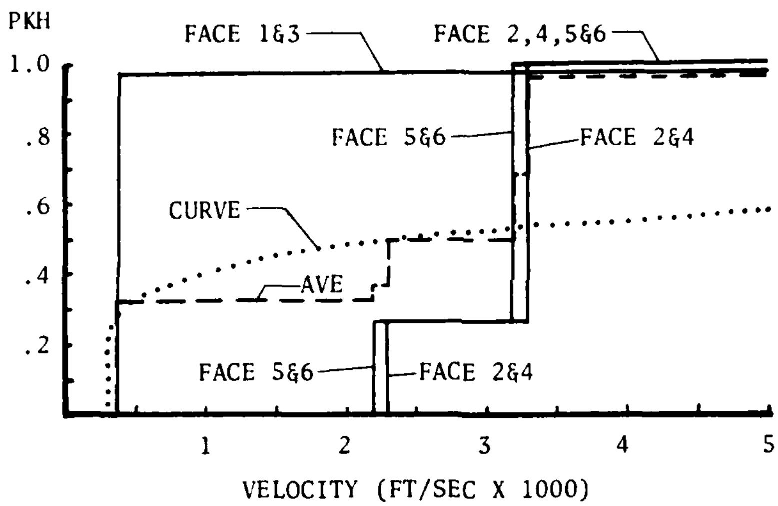
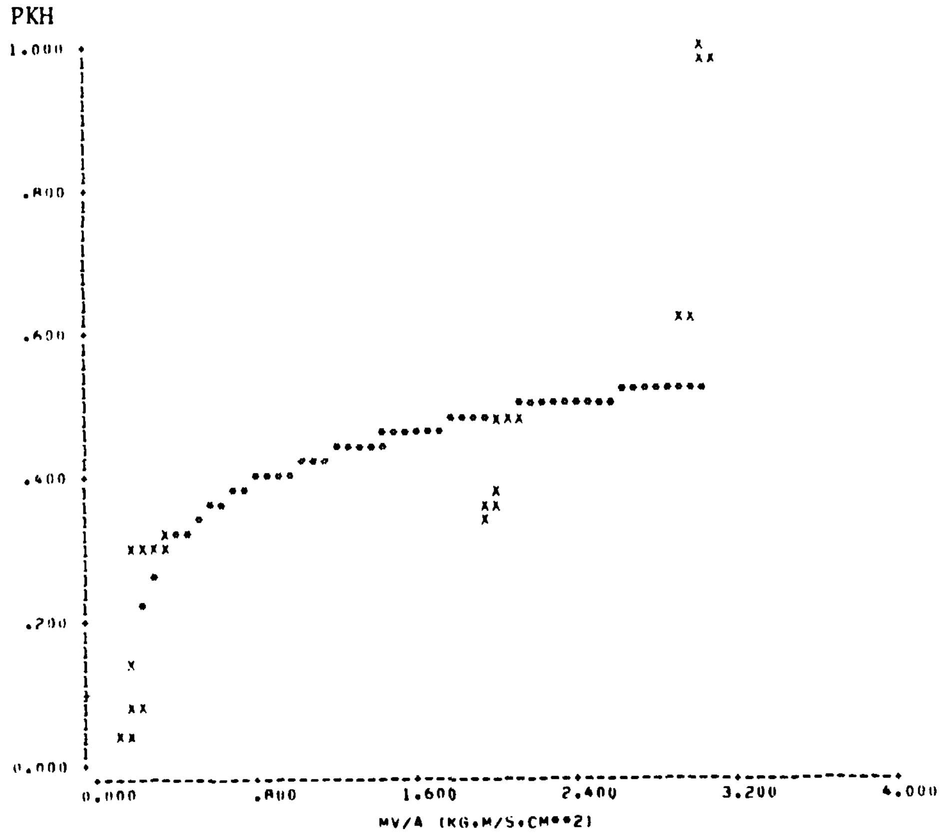
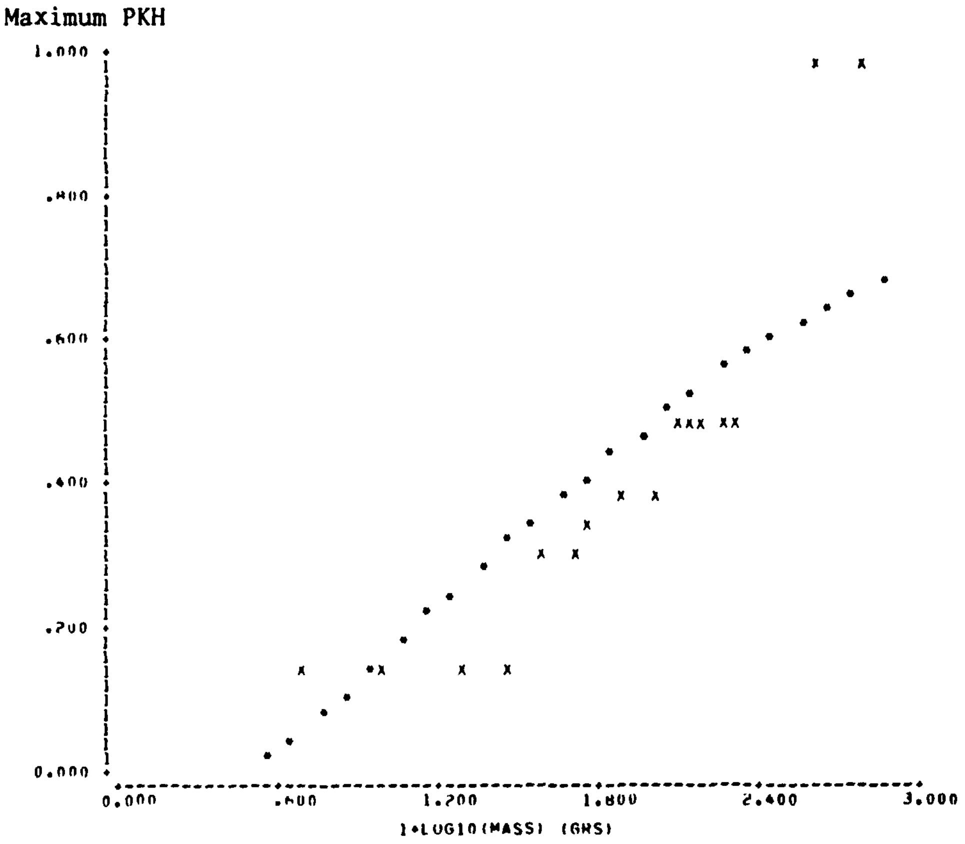


Figure 2. (Continued)



X - Indicates MV/A Data Point
* - Indicates Curve Fit Point

Figure 3. GENREG Regression Curve Fit for the M48A1 Tank Engine/Transmission Oil Cooler (FSF=.0145)



X - Indicates 1+Log_{10}(Mass) Data Point
* - Indicates Curve Fit Point

Figure 4. MAXFIT Regression Curve Fit for the M48A1 Tank Engine/Transmission Oil Cooler (FSF=.0145)

In Figures 5 and 6 the GENREG and MAXFIT regression curves are presented for this component when struck by a fragment with shape factor .0077. It will be noted that there is even more scatter in the MV/A data in Figure 5 indicating even poorer PKH predictions for this fragment shape factor.

The curve fit PKH's shown in Figure 2(a-q) were not very representative of the average PKH step functions. A brief investigation of curve fits for individual face PKH's was made and the results are presented in Figure 7. Individual "curve" fit and step function PKH's for each face were plotted as a function of fragment striking velocity for the 8.0- and 80.0-grain fragments.

The results in Figure 7a indicate that the curve fits for Faces 1 and 3 are good and for Faces 2, 4, 5, and 6, fair. In Figure 7b the results show again that the curve fits for Faces 1 and 3 are good; however, those for Faces 2 and 4 are not so good from 2300 to 3500 ft/sec and those for Faces 5 and 6 are bad from 2300 to 5000 ft/sec.

The above face-to-face variation in results was based on only one component. In order to determine how many M48A1 Tank components might be categorized as nonhomogeneous, nonsymmetrical types, the PKHDOC program was used to compute the *minimum mass* capable of producing a non-zero PKH (i.e., satisfy the kill hole diameter and barrier penetration requirements) on each face of the 129 identifiable (non-redundant) M48A1 Tank components* (excluding crew members) for optimum velocities less than or equal to 5000 ft/sec. For each component, the *minimum masses* calculated for each face were averaged and the standard deviation of this average was computed. The standard deviation, or deviation about the mean minimum fragment mass for the component, was expressed as percent deviation about the mean. The percent deviation for the sample component was approximately 53%. Of the 129 M48A1 Tank components, 29 had deviations of 53% or greater (53 to 238%); 16 had deviations of from 14% to 52%. The remaining 84 components were truly homogeneous, symmetrical components with no face-to-face variation. Figure 8 is a histogram of percent deviations about the mean *minimum* mass capable of killing each face of an M48 Tank component.

C. *Conclusions*

Although this was a very limited study in which only one representative component was sampled, the following conclusions have been reached.

1. Face-to-face PKH variations can be considerable for nonhomogeneous, nonsymmetrical type components. The computation of a PKH averaged over all component faces can result in a PKH which decreases the vulnerability of the most vulnerable faces and increases the vulnerability of the last vulnerable faces. This results in a significant misrepresentation of the component's vulnerability to certain mass/velocity combinations for specific attack directions. For example the Engine/Transmission Oil Cooler with PKH's

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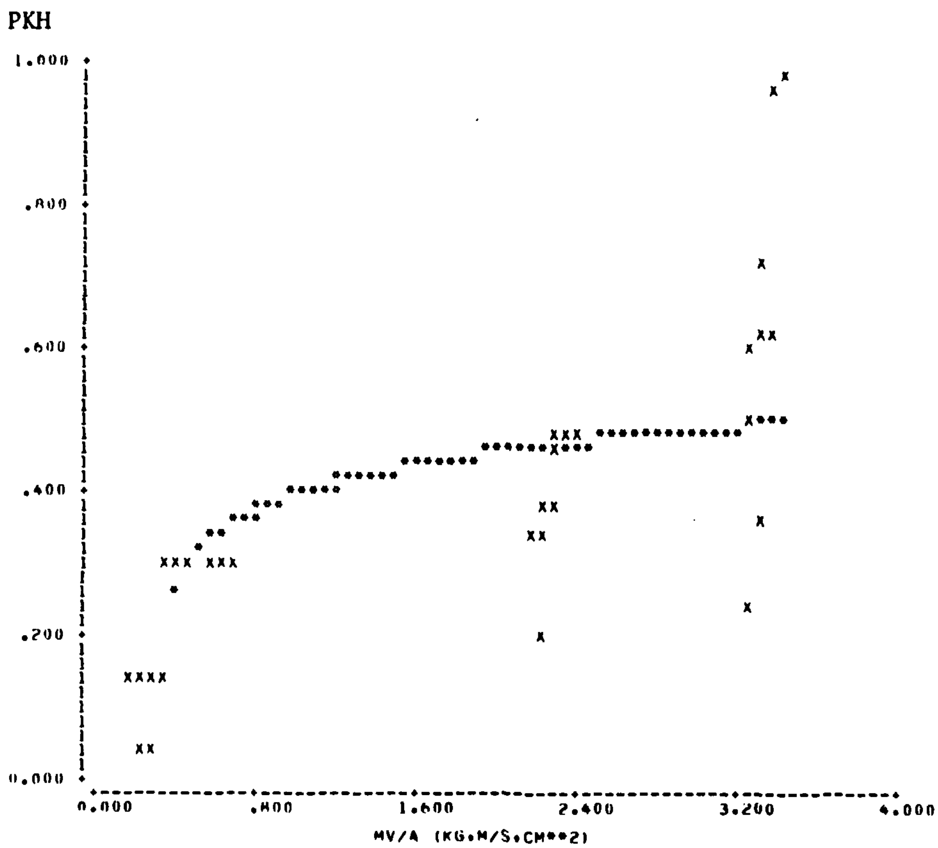
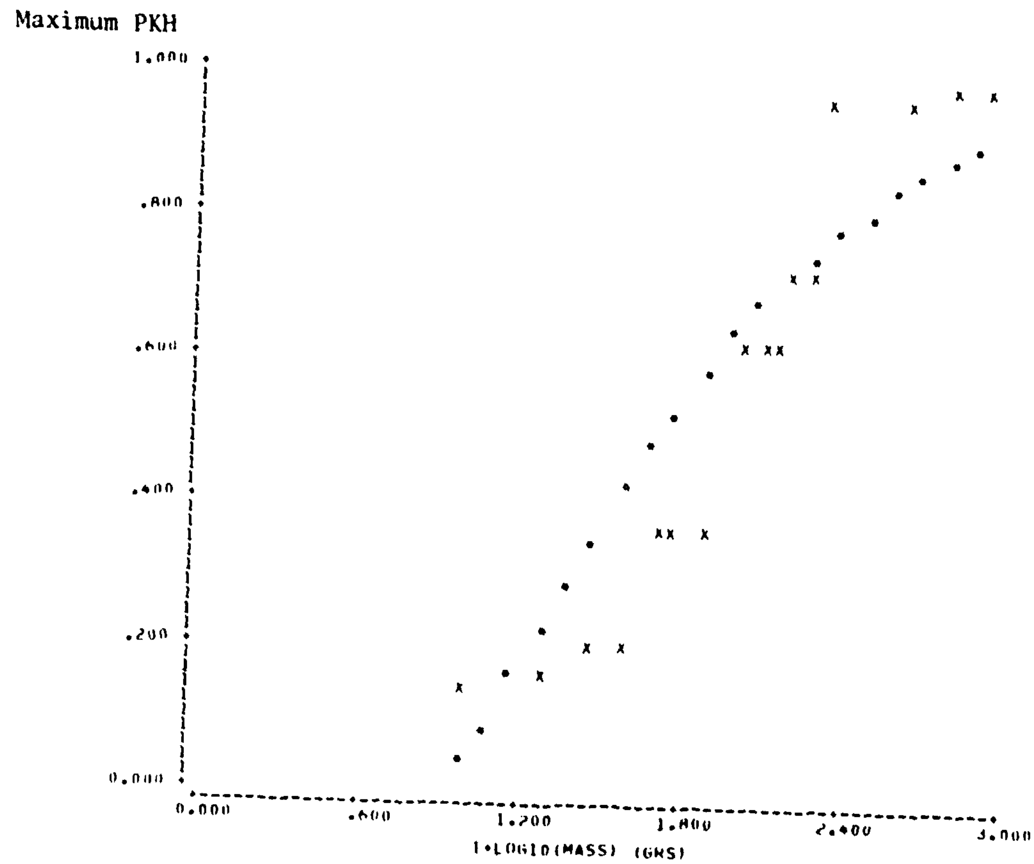
* R. E. Kinsler and G. L. Durfee, "Analytical Probabilities of Kill for Compact Fragment Impact on Components of the M48A1 Tank," Ballistic Research Laboratory, Report in Preparation.



X - Indicates MV/A Data Point
* - Indicates Curve Fit Point

Figure 5. GENREG Regression Curve Fit for the M48A1 Tank Engine/Transmission Oil Cooler (FSF=.0077)



X - Indicates $1+Log_{10}$(Mass) Data Point

* - Indicates Curve Fit Point

Figure 6. MAXFIT Regression Curve Fit for the M48A1 Tank Engine/Transmission Oil Cooler (FSF=.0077)

Fig. 7(a) - 8.0 Grains

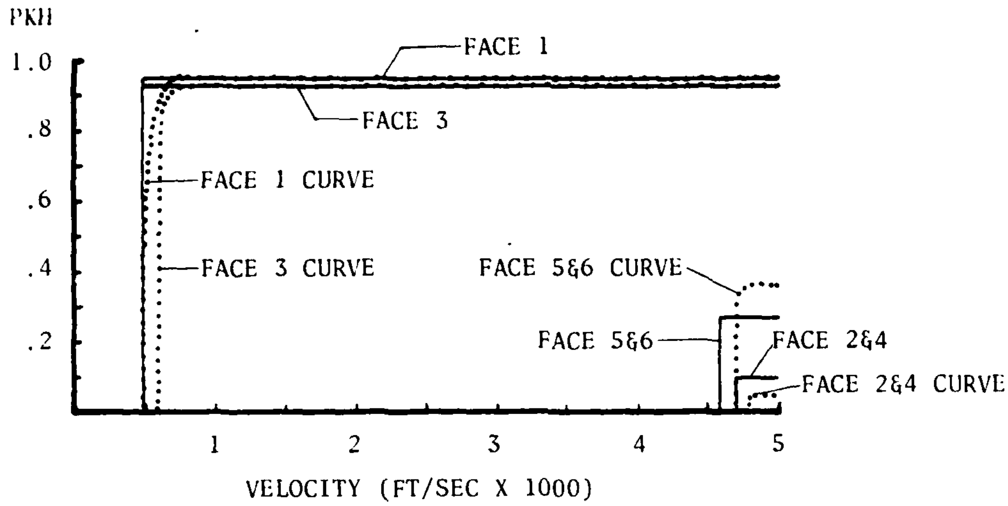


Fig. 7(b) - 80.0 Grains

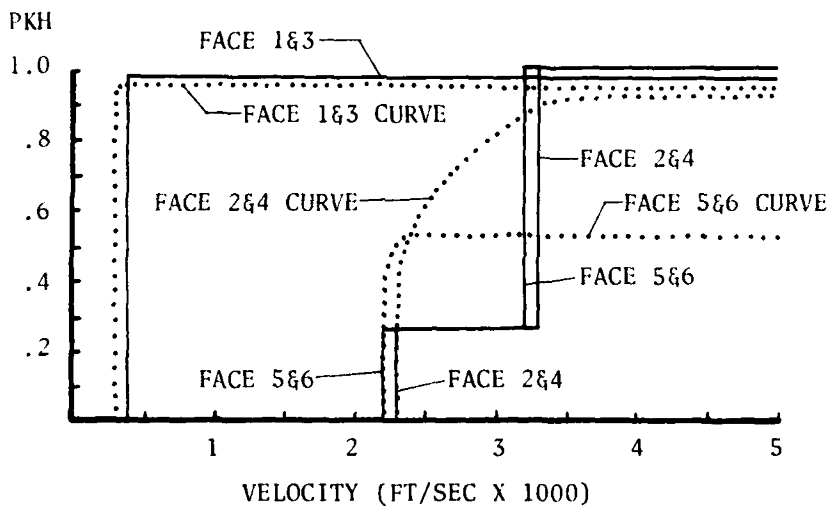


Figure 7. Comparison of PKH's of Individual Faces (M48A1 Tank Engine/Transmission Oil Cooler) with GENREG/MAXFIT Curve Fit for Each Face

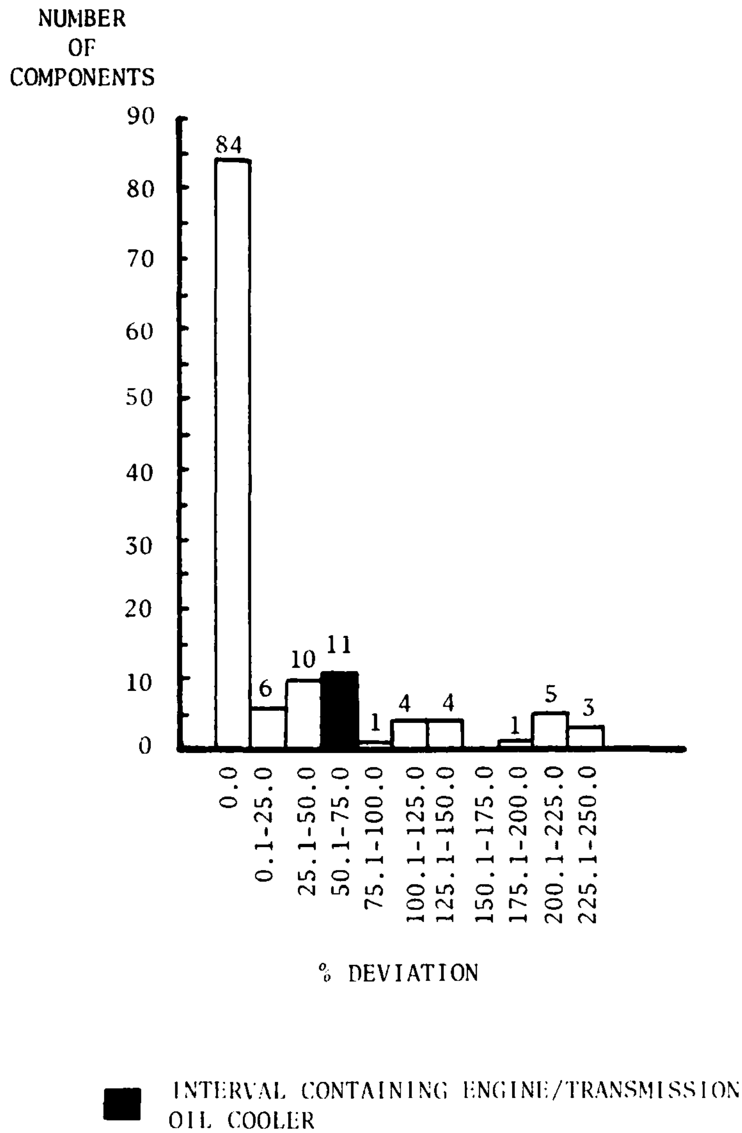


Figure 8. Histogram of Per Cent Deviations about the Mean Minimum Mass Capable of Killing Each Face of an M48A1 Tank Component

of .92 for one face and 0.0 for its other five faces is represented by an "average" PKH of .15 irrespective of attack direction.

2. Present curve fitting routines do not do a good job of representing the PKH step functions (averaged over all component face) for this type component. For example the GENREG/MAXFIT curve predicts a 0.0 PKH for the component having a .92 PKH for one face and 0.0 PKH's for the other five faces (for a specific fragment mass/velocity combination). (Fragment momentum per average fragment presented area (MV/A), as presently used in the curve fitting routines, does not correlate well with PKH for components of this type). These curve fitting routines do little better in representing the PKH step functions for each component face, except where the PKH is constant (one step). Presumably, if there were many small steps in the PKH functions, the curve fit would be better.

D. *Recommendations*

Our recommendations are as follows:

1. Investigations should commence to determine the feasibility of modifying the current point-burst model to accommodate a routine for face-to-face PKH variation for specific components based on attack direction. These modifications might include software changes to compute the required component PKH as needed (i.e., only when the component is hit), or to access a precomputed table of PKH's for killing mass/velocity combinations developed for individual attack directions. Certain homogeneous, symmetric components could still utilize an average PKH (one number for all faces).

2. A point-burst model sensitivity analysis should be performed to determine just how much variation in face-to-face component PKH is allowable. It might be established, for example, that a variation of ±20% in component face-to-face PKH might result in acceptable variation in the output of a point-burst model. If so, then all components with less than ±20% variation could be assigned their respective average PKH's. However, components with more than ±20% PKH variation would be treated as being sensitive to attack direction and would require PKH's for each of their respective faces.

3. Until such time that methodology for determining face-to-face component PKH is developed for use in the point-burst model, component PKH's generated by PKHDOC should be scrutinized for misrepresentation in GENREG/MAXFIT curve fits and PKH step functions* should be utilized as inputs to the point-burst model.

* Some later versions of the PKHDOC program include 2- and 4-step step-function values to represent the PKH's generated by PKHDOC. Although these 2- and 4-step step-functions do not account for face-to-face PKH variations, they may do a better job of representing the component average PKH (average over six faces) than does the GENREG/MAXFIT curve combination.

V. SENSITIVITY TO FRAGMENT SHAPE FACTOR

A. *Method*

In the PKHDOC program, the shape of the fragment striking a component may play an important part in determining the component's vulnerability. When a fragment strikes the sensitive area of a critical component, the size of the hole it makes is compared with the size of the evaluator's predicted "kill" hole. If the hole made by the striking fragment is larger than that required for a kill, the sensitive area is killed and a PKH computed for the component.

The present method for determining the size of the impacting fragment (and by implication the hole size it produces) is given by the following equation:

$$A_f = KM_s^{2/3} \tag{1}$$

where A_f is the average presented area (inches^2) for random orientation of the fragment, K is the fragment shape factor* (inches^2/grains$^{2/3}$) and M_S is the striking mass (grains) of the fragment. Rearranging terms in equation 1 gives:

$$M_s = \left(\frac{A_f}{K}\right)^{3/2} \tag{2}$$

and we see that for a specified A_f to kill a sensitive area, the fragment striking mass required to make this hole increases as the fragment shape factor (FSF) decreases. Thus, if, for example, $A_f = 0.13$ inches^2 , then $M_s \simeq 69$ grains for FSF = .0077 and $M_s \approx 27$ grains for FSF = .0145. Although a 27 grain fragment with FSF = .0145 can meet the specified kill hole requirement (0.13 inches^2), it is quite possible that for a given velocity it will not be able to penetrate into the sensitive area. Fragment penetration is given by the THOR equations below:

$$M_r = M_s - 10^{a_1}\left(tK\right)^{a_2} M_s^{\left(a_3 + \frac{2a_2}{3}\right)} \operatorname{Sec}\theta^{a_4} V_s^{a_5} \tag{3}$$

$$V_r = V_s - 10^{b_1}\left(tK\right)^{b_2} M_s^{\left(b_3 + \frac{2b_2}{3}\right)} \operatorname{Sec}\theta^{b_4} V_s^{b_5} \tag{4}$$

---

* Fragment shape factor (FSF) is a function of both fragment geometry and material type. If equation 1 is solved for FSF, i.e., K, the result is

$$K = \frac{A_f}{\left(M_s\right)^{2/3}}$$

But fragment mass, M_s, is given by $\rho\, V_f$ where ρ is fragment mass density and V_f is fragment volume. Therefore,

$$K = \frac{A_f}{\left(\rho V_f\right)^{2/3}}$$

where A_f and V_f vary with fragment geometry and ρ varies with fragment material type. In this report the FSF's were derived for steel fragments ($\rho = 1.988 \times 10^3$ grains/inches^3).

where:

M_r	=	residual mass (grains)
M_s	=	striking mass (grains)
a_1-a_5,b_1-b_5	=	THOR constants (based on material type)
t	=	barrier thickness (inches)
V_s	=	fragment striking velocity (ft/sec)
V_r	=	fragment residual velocity (ft/sec)
K	=	fragment shape factor ($inches^2/grains^{2/3}$)
θ	=	striking obliquity angle (degrees)

Thus in equation 4 it will be noted that the .0077 (smaller) FSF is a more efficient penetrator when b_2 is positive (as was the case for the materials of the component investigated) in that there is less degradation to the striking velocity, V_s, resulting in a larger residual velocity, V_r. (In the PKHDOC program, a minimum V_r of 300 ft/sec is required before a penetration is assumed). Also, where there are several barriers and a_2 is positive, there is less degradation to striking mass, M_s (i.e., less mass lost from the fragment as it penetrates the barrier) for the smaller FSF (.0077), resulting in a larger residual mass, M_r (i.e., more mass is available to make a hole in the sensitive area). Therefore, a fragment's ability to kill a component is sensitive to FSF; this enters into the calculation of component kill in two divergent ways. A fragment with a large FSF can produce large holes (to meet kill requirement for large holes in the sensitive area), and one with a small FSF is a more efficient penetrator (to get through the barriers and into the sensitive area).

In order to quantify PKHDOC component variations in PKH as a function of variations in FSF, the PKHDOC program was exercised for the M48A1 Tank Engine/Transmission Oil Cooler for fragment velocities up to 5000 ft/sec and for the fragment masses given in Table 2. The average PKH (over all six faces) for the component was computed for the .0077 (spherical) and .0145 (random artillery fragment) shape factors. The PKH's were also computed for each face of the component for both shape factors. The calculated average PKH's, the PKH's from the curve fit routine (GENREG/MAXFIT combination), and calculated PKH's for individual component faces for both shape factors were compared. We also computed the minimum mass capable of killing each component face (penetrating a sensitive area and making a hole sufficient to kill the sensitive area) at the optimum* velocity less than or equal to 5000 ft/sec.

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* When utilizing the THOR equations (equation 3 & 4) to determine fragment residual velocity and residual mass (after penetrating a barrier), it is found that, in general, increasing fragment velocity allows a fragment with smaller mass to successfully penetrate the barrier. Conversely, decreasing fragment velocity results in a larger fragment mass being required to achieve a successful penetration.

However, an "optimum" velocity (associated with a "minimum" fragment mass) capable of penetrating and killing the component results from some combinations of material type, multiple barrier, and kill hole requirement. If the fragment velocity is increased beyond the optimum, the fragment mass required for a successful kill also increases.

In this study a maximum fragment velocity of 5000 ft/sec was allowed, and the PKHDOC program was used to compute the minimum mass capable of killing a component face at this optimum velocity. Therefore, throughout this report, the optimum velocity is 5000 ft/sec unless otherwise stated.

B. *Results*

A comparison of the effects of FSF variations on component PKH as a function of striking velocity for a given mass is presented in Figure 9. In Figure 9(a-q) the average PKH step functions (average over six faces) are labeled ".0145 AVE" and ".0077 AVE." The curve fits, derived for the specific indicated mass from the GENREG/MAXFIT regression curve combination, as explained earlier, are labeled ".0145 CURVE." and ".0077 CURVE."

Figure 9f indicates that for a fragment with a mass of 5.0 grains and a velocity of 2500 ft/sec the average computed PKH is .15 for the .0077 FSF and .30 for the .0145 FSF. The .0077 FSF curve gives a PKH of .44, and the .0145 curve gives a PKH of .39.

Figure 9n indicates that for a fragment with a mass of 20.0 grains and a velocity of 3200 ft/sec the average computed PKH is .95 for the .0077 FSF and .30 for the .0145 FSF. The .0077 curve gives a PKH of .50, and the .0145 FSF curve gives a PKH of .48.

An inspection of the other plots in Figure 9 indicate results similar to those above. In general, the average computed step function for PKH for this component exhibits significant sensitivity to variation in FSF for many of the mass/velocity combinations considered. However, the curves (see Figure 9) derived from the GENREG/MAXFIT curve combination are not only poor representations of the average PKH step functions, but also show very little sensitivity to variations in FSF (from .0077 to .0145).

A comparison of the effects of variations in FSF on the PKH of each component face as a function of striking velocity for a given mass is presented in Figure 10. In Figure 10(a-p) the PKH (computed step function) for each of the six component faces is identified by a dashed line for the .0145 FSF and a solid line for the .0077 FSF. Each step function is labeled by the corresponding component face number. Superimposed over these step functions are the average PKH curves from Figure 9.

We showed earlier in this report that the averaging of this component's faces renders it insensitive to attack direction. This is indicated again in Figure 10 when the curves for each component face are compared with the step function PKH's.

In Figure 10(a-h) it can be seen that Face 1 is equally vulnerable to most mass (1.0 to 10.0 grain) and velocity (700 to 5000 ft/sec) combinations irrespective of shape factor. The component data for Face 1 (Table 1) indicate that a kill is obtained by putting a very small hole (0.09-inch diameter) in a very thin material (0.01 inch). However, Face 3 shows much more sensitivity to FSF. The results in Figure 10(d-h) indicate that Face 3 can be killed by a 4.0-grain fragment with a .0145 shape factor, but a fragment with a shape factor of .0077 must have a mass of at least 10 grains in order to kill the sensitive area of this face. The component data indicate that although Faces 1 and 3 have the same material types and thicknesses, the hole diameter required to kill the sensitive areas are different (0.09-inch diameter for Face 1, 0.20-inch diameter for Face 3). Thus the larger shape factor (.0145) can meet the size requirement for kill hole with a smaller fragment mass. This means that if Face 3 of this component is exposed to a spall distribution with maximum fragment mass of 5.0 grains, for example, then the face is not vulnerable to spall with FSF = .0077, but is vulnerable to spall with FSF = .0145 (for a single fragment impact).

Fig. 9(a) - 0.5 Grain

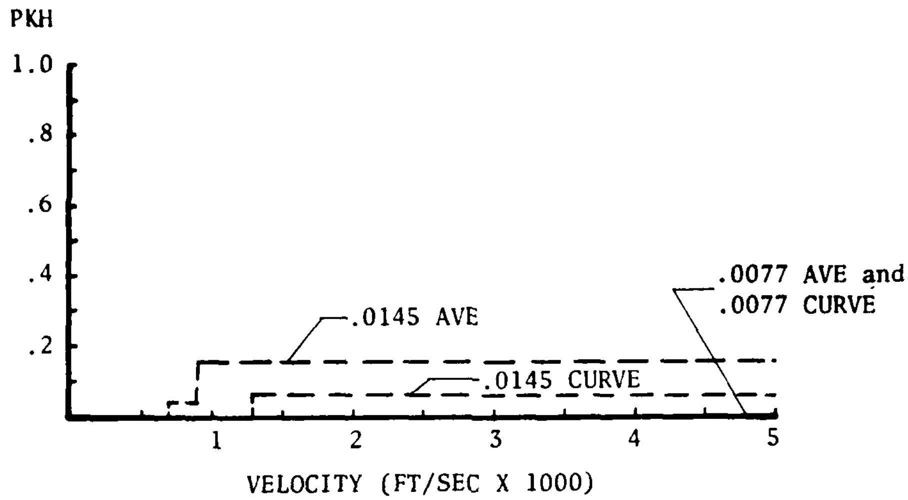
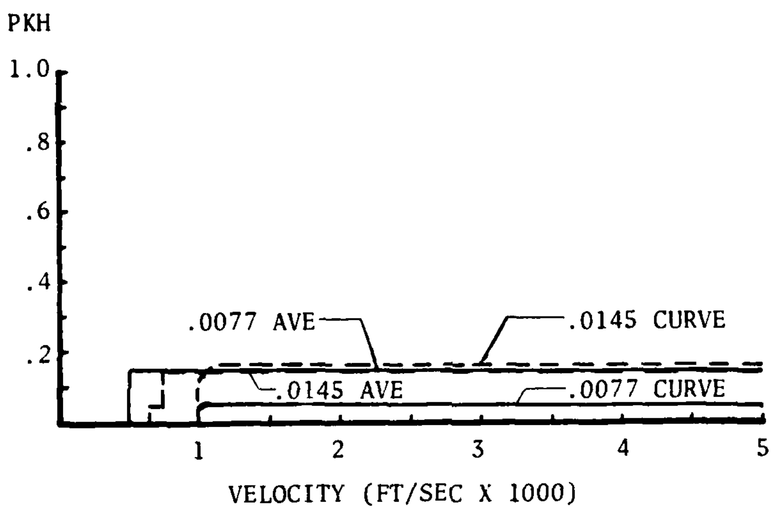


Fig. 9(b) - 1.0 Grain



——————— .0077 FRAGMENT SHAPE FACTOR

— — — — — — — .0145 FRAGMENT SHAPE FACTOR

Figure 9. Probabilities of Kill (Given a Hit) as a Function of Velocity and Fragment Shape Factor for Given Fragment Masses for the M48A1 Tank Engine/Transmission Oil Cooler

Fig. 9(c) - 2.0 Grains

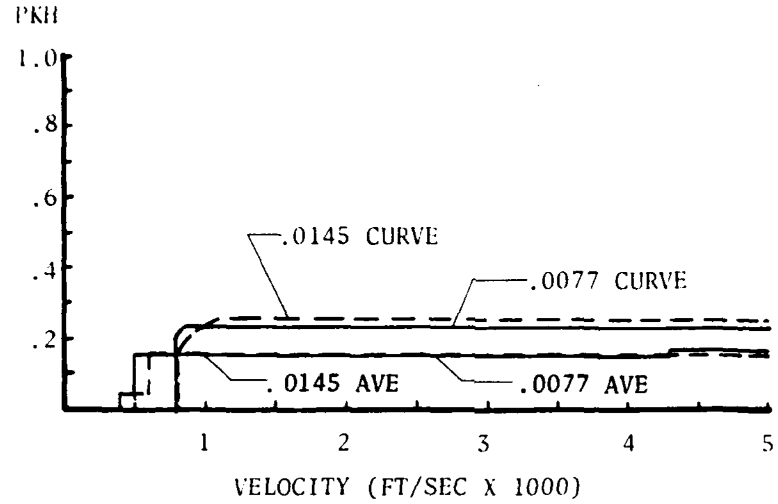
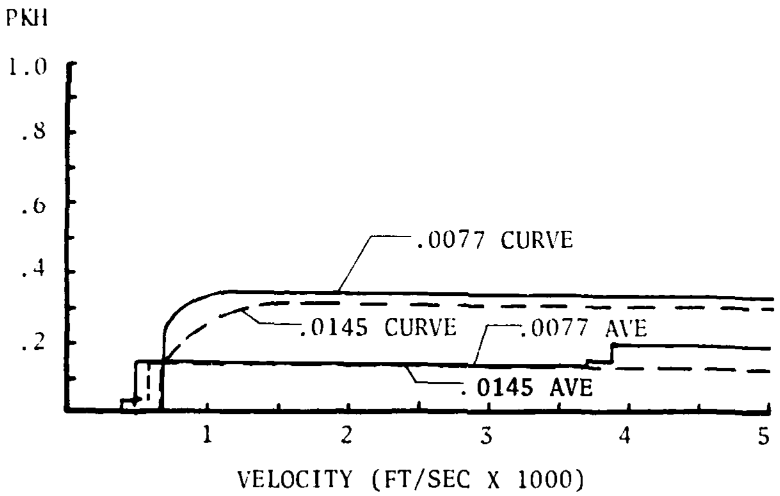


Fig. 9(d) - 3.0 Grains



.0077 FRAGMENT SHAPE FACTOR

.0145 FRAGMENT SHAPE FACTOR

Figure 9. (Continued)

Fig. 9(e) - 4.0 Grains

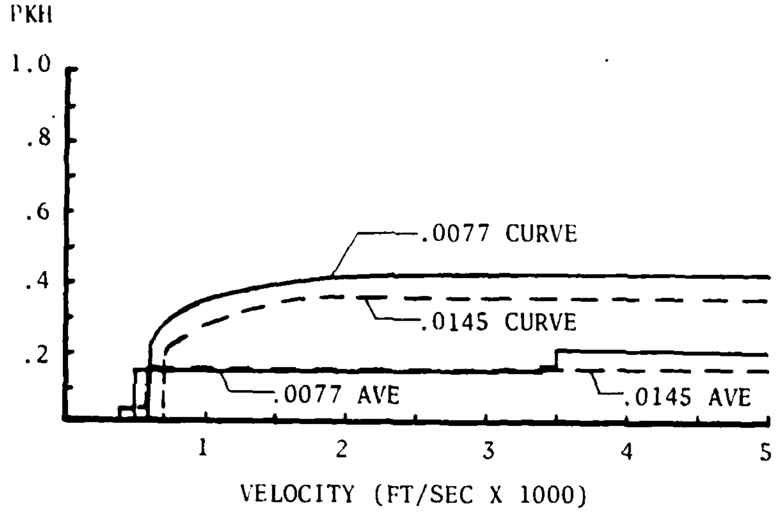
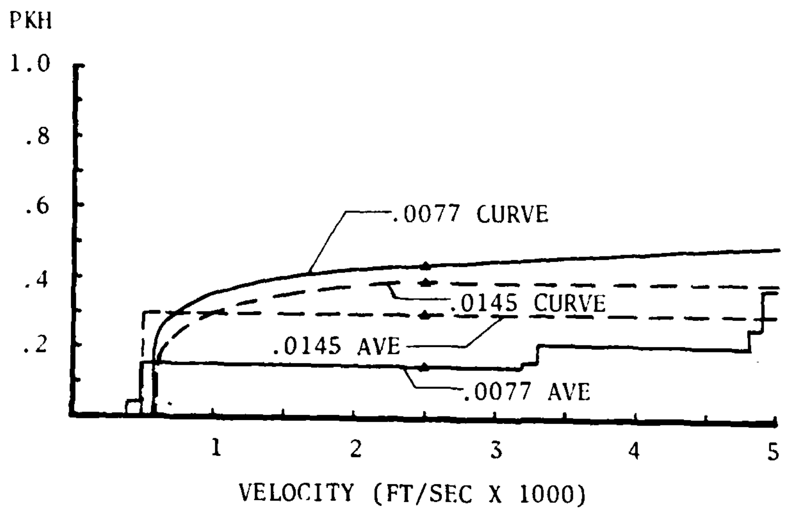


Fig. 9(f) - 5.0 Grains



△ INDICATES DATA POINT REFERENCED IN TEXT

——————— .0077 FRAGMENT SHAPE FACTOR

— — — — — — .0145 FRAGMENT SHAPE FACTOR

Figure 9. (Continued)

Fig. 9(g) - 6.0 Grains

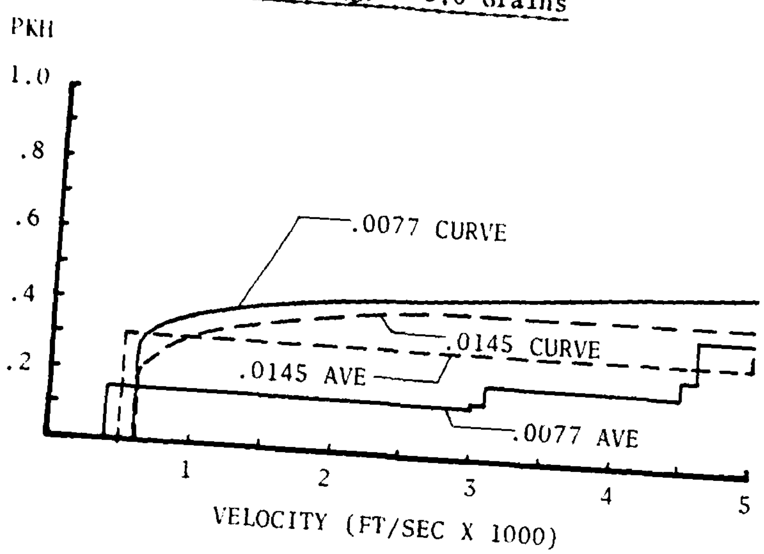


Fig. 9(h) - 8.0 Grains

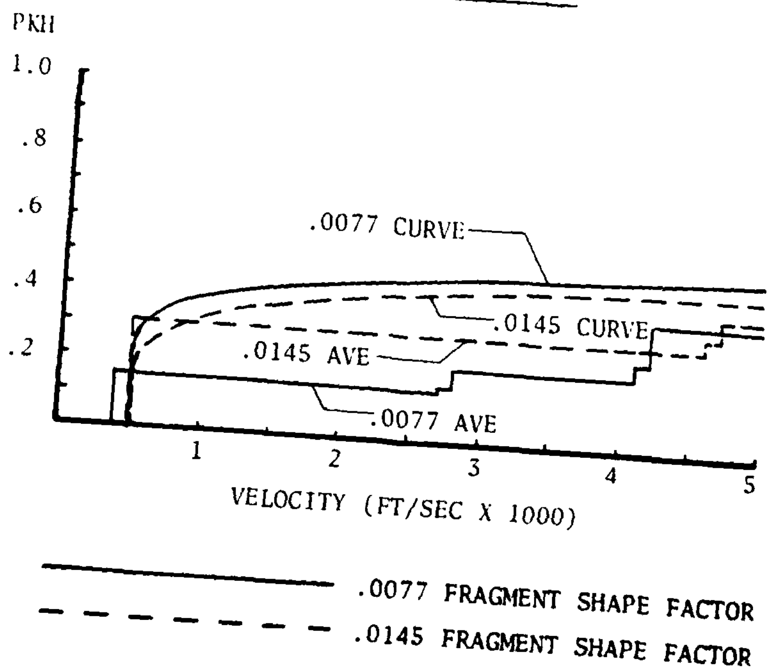


Figure 9. (Continued)

Fig. 9(i) - 10.0 Grains

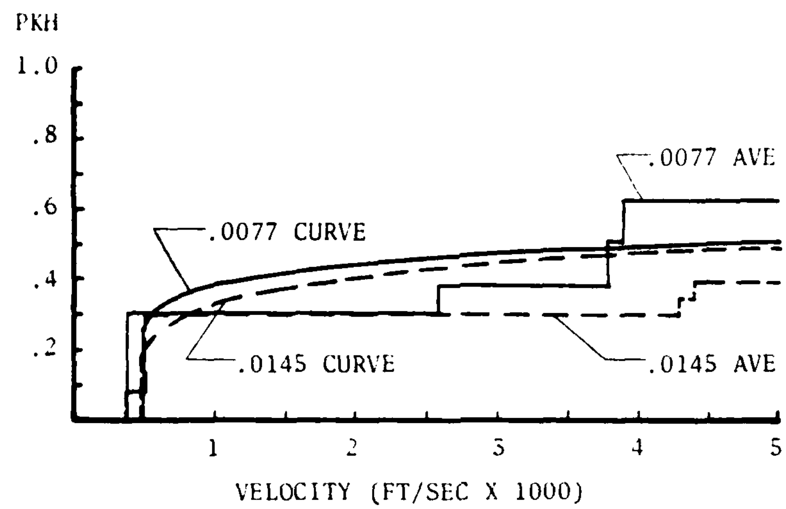
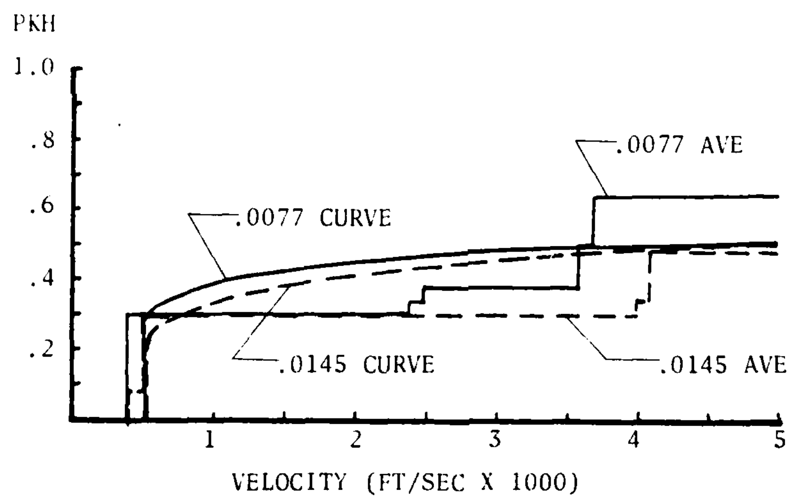


Fig. 9(j) - 12.0 Grains



.0077 FRAGMENT SHAPE FACTOR

.0145 FRAGMENT SHAPE FACTOR

Figure 9. (Continued)

Fig, 9(k) - 14.0 Grains

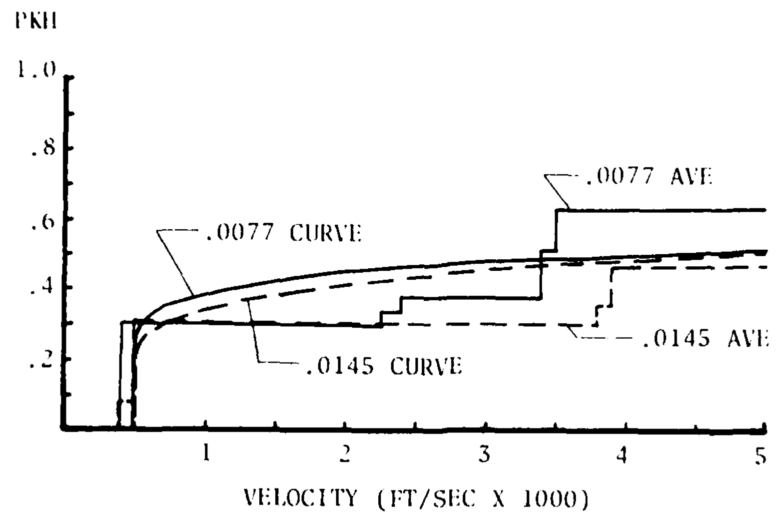


Fig. 9(l) - 16.0 Grains

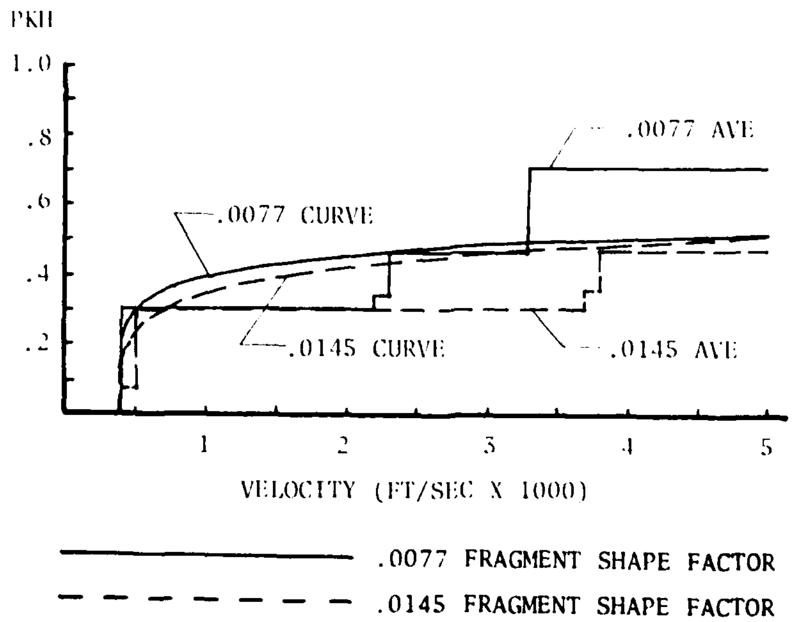


Figure 9. (Continued)

Fig. 9(m) - 18.0 Grains

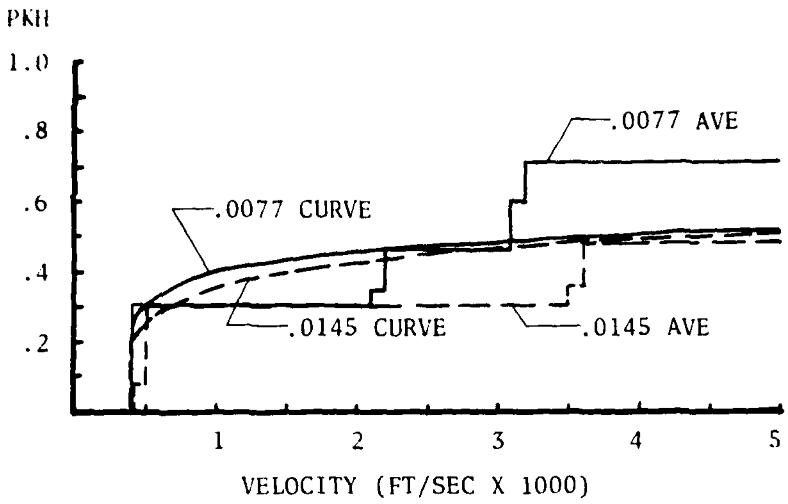
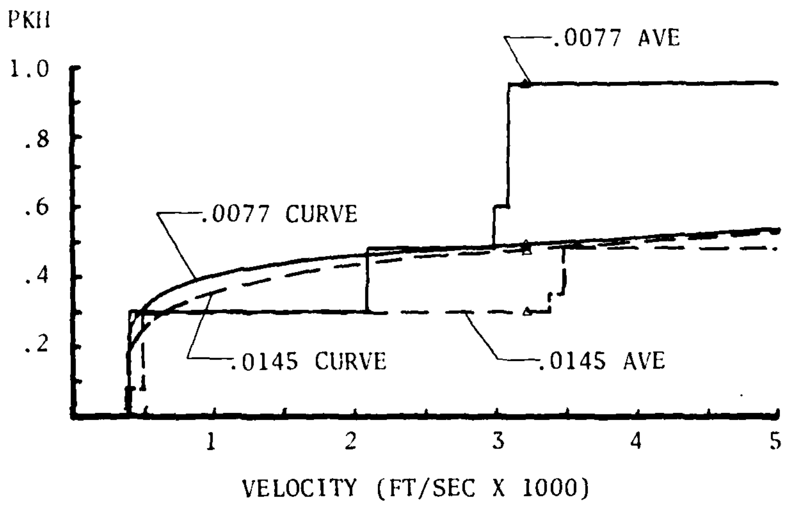


Fig. 9(n) - 20.0 Grains



▵ INDICATES DATA POINT REFERENCED IN TEXT

——————— .0077 FRAGMENT SHAPE FACTOR

— — — — — — — .0145 FRAGMENT SHAPE FACTOR

Figure 9. (Continued)

Fig. 9(o) - 40.0 Grains

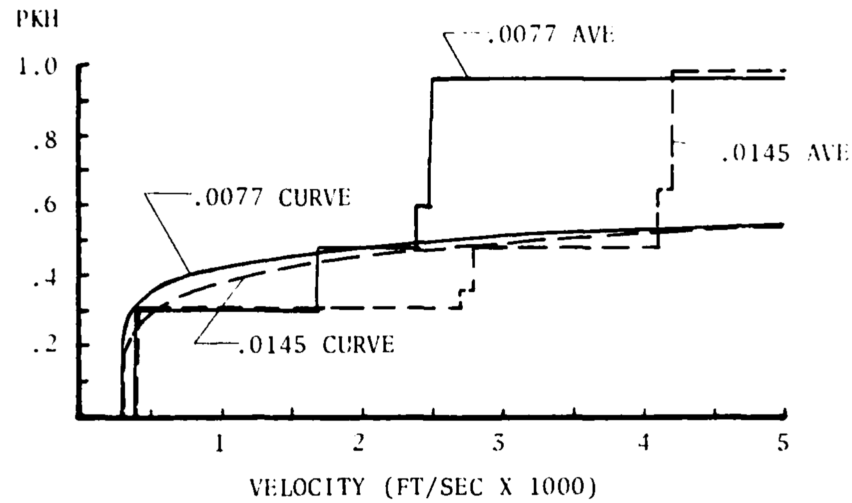


Fig. 9(p) - 60.0 Grains

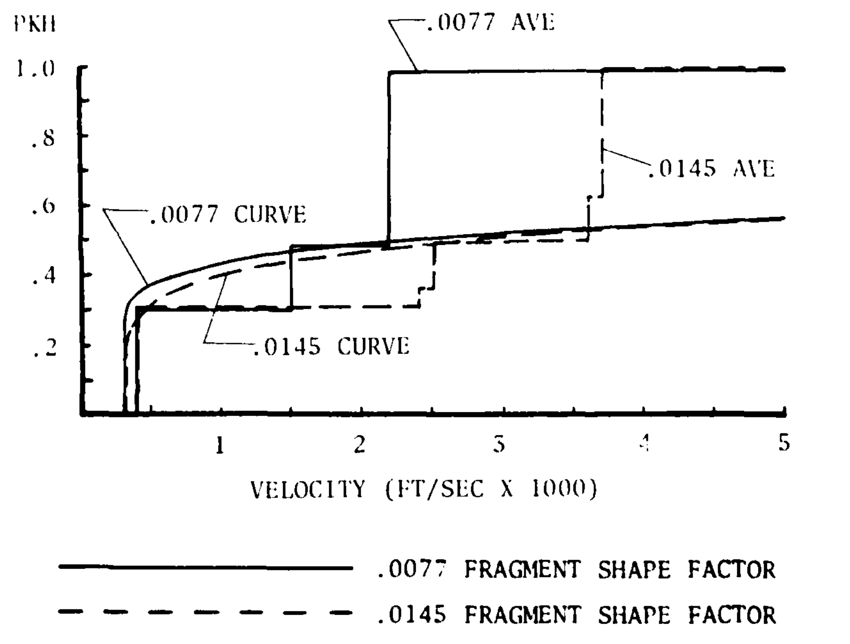


Figure 9. (Continued)

Fig. 9(q) - 80.0 Grains

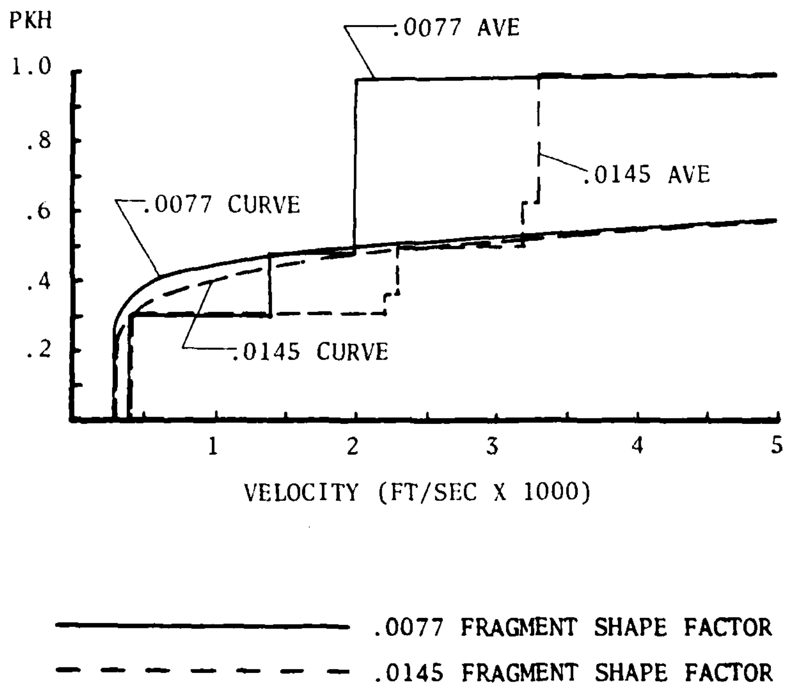


Figure 9. (Continued)

Fig. 10(a) - 1.0 Grains

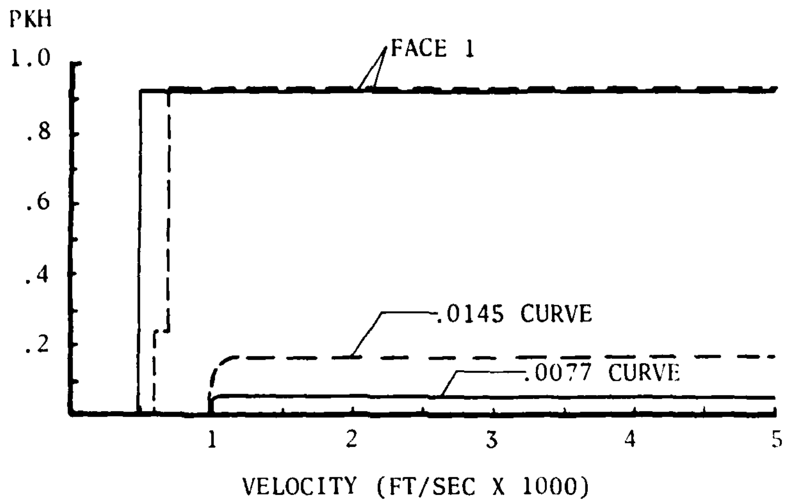


Fig. 10(b) - 2.0 Grains

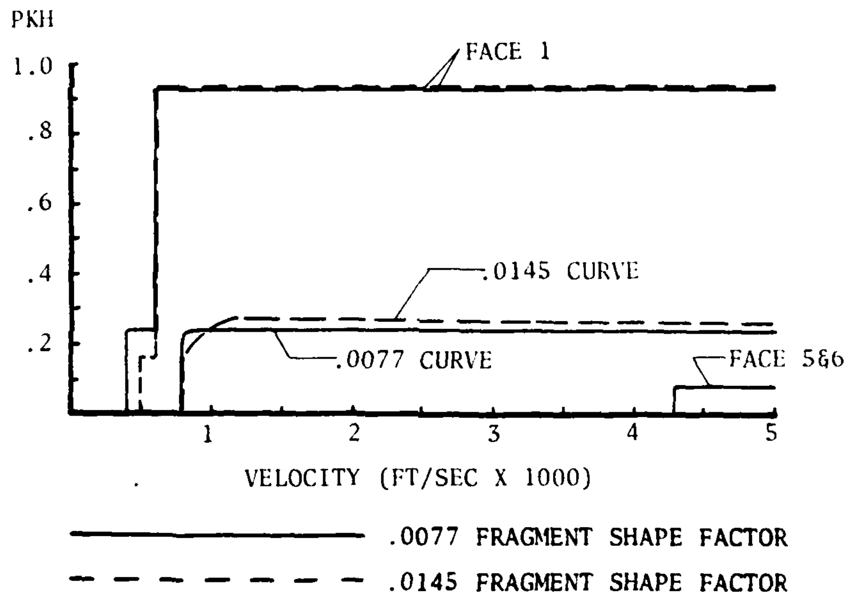


Figure 10. **Probabilities of Kill (Given a Hit) for Individual Faces of the M48A1 Tank Engine/Transmission Oil Cooler as a Function of Velocity and Fragment Shape Factor for Given Fragment Masses**

Fig. 10(c) - 3.0 Grains

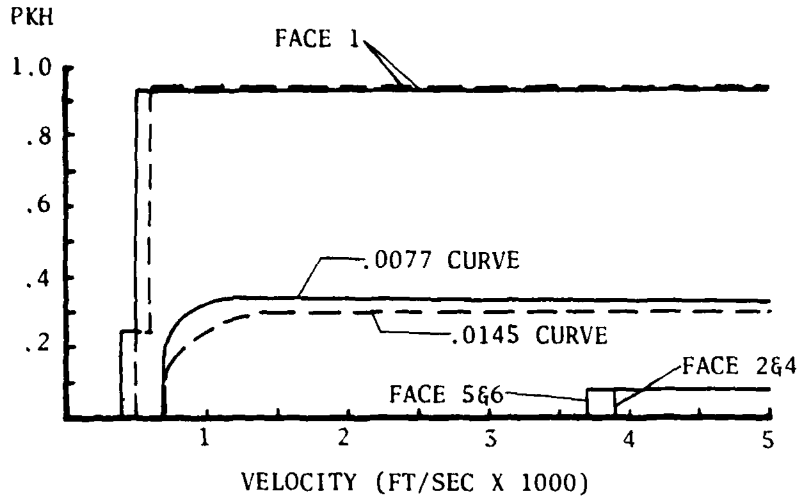
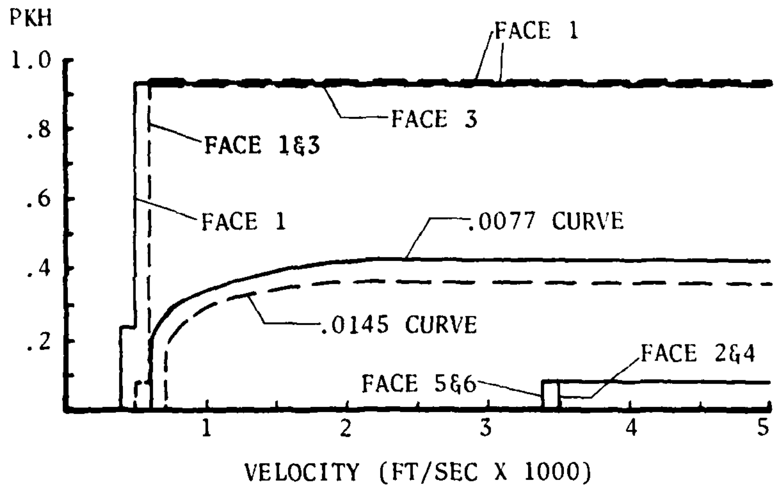


Fig. 10(d) - 4.0 Grains



———— .0077 FRAGMENT SHAPE FACTOR

– – – – .0145 FRAGMENT SHAPE FACTOR

Figure 10. (Continued)

Fig. 10(e) - 5.0 Grains

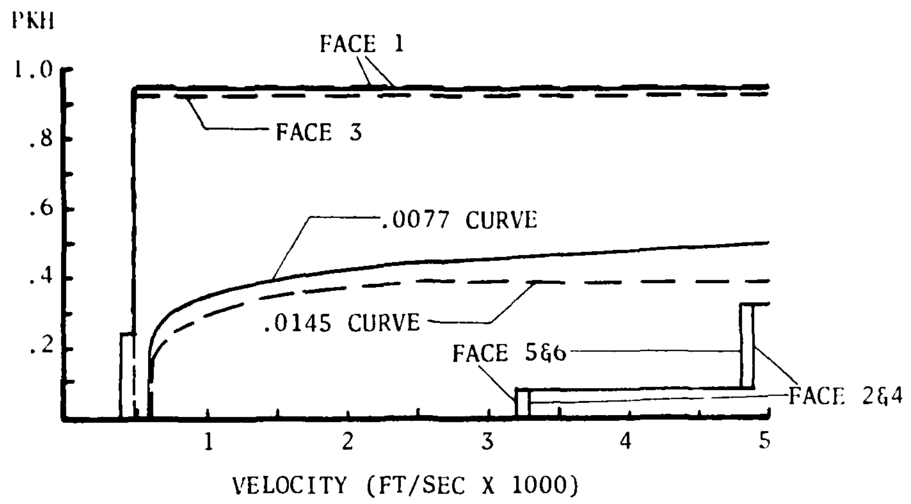


Fig. 10(f) - 6.0 Grains

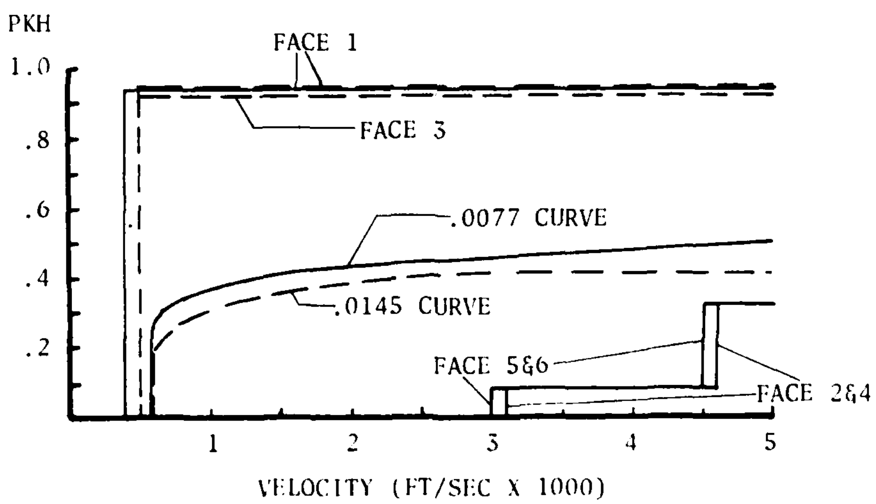


Figure 10. (Continued)

Fig. 10(g) - 8.0 Grains

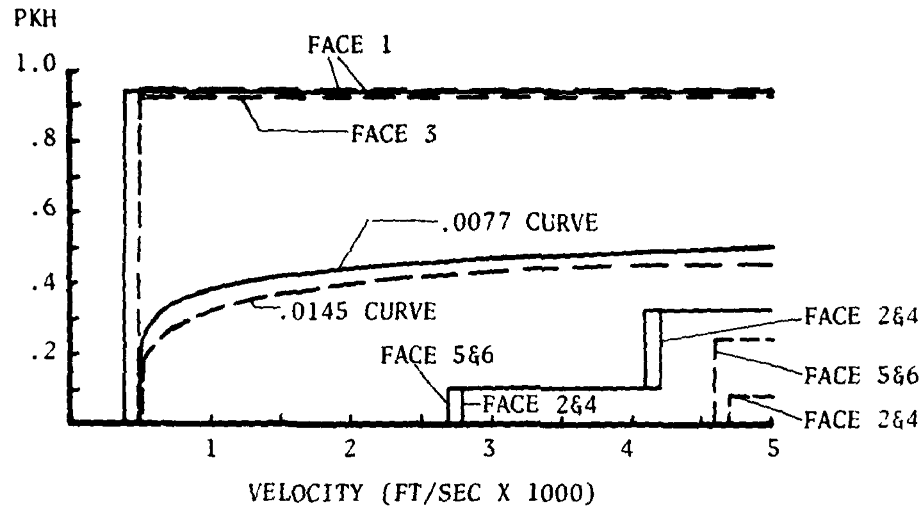
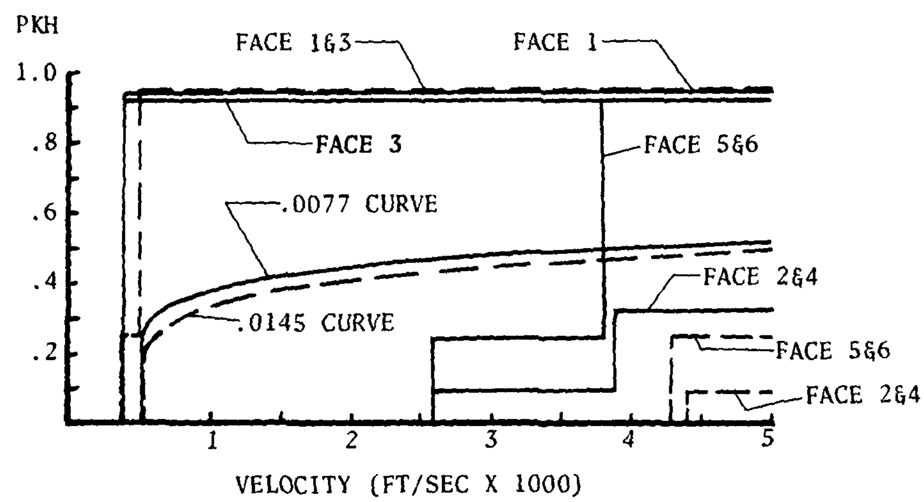


Fig. 10(h) - 10.0 Grains



———— .0077 FRAGMENT SHAPE FACTOR

– – – – .0145 FRAGMENT SHAPE FACTOR

Figure 10. (Continued)

Fig. 10(i) - 12.0 Grains

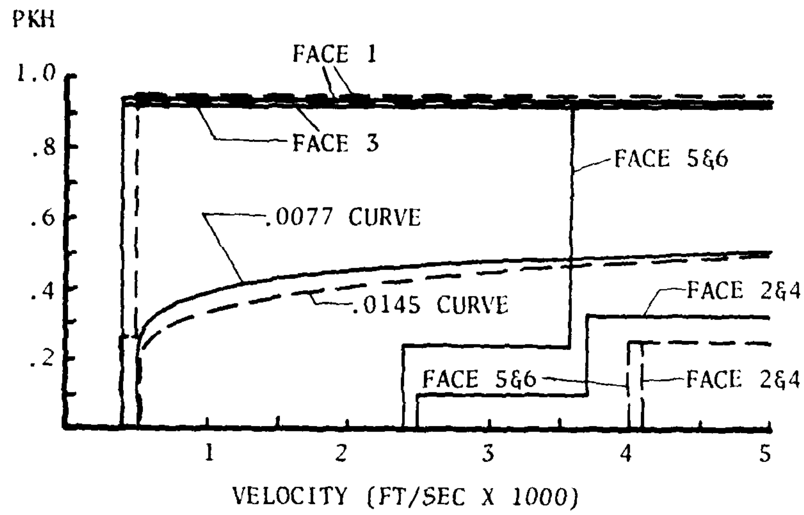


Fig. 10(j) - 14.0 Grains

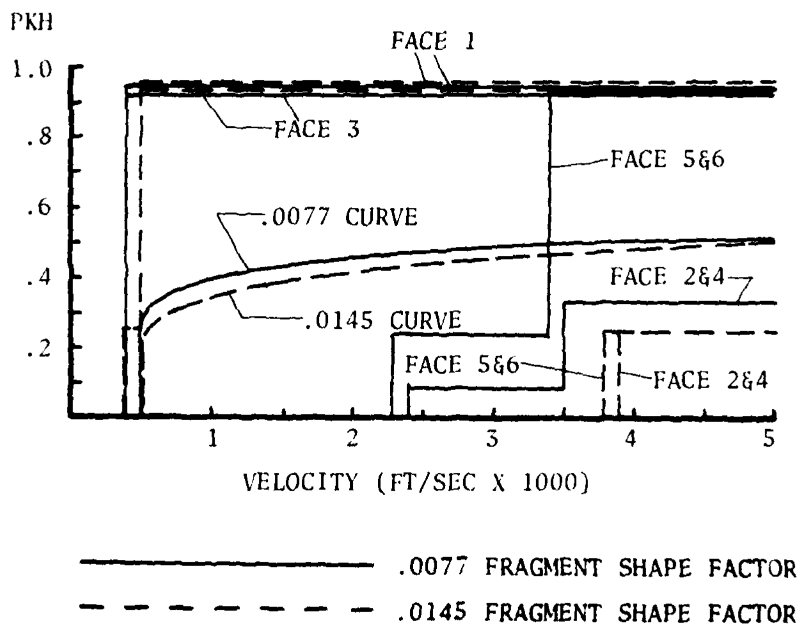


Figure 10. (Continued)

Fig. 10(k) - 16.0 Grains

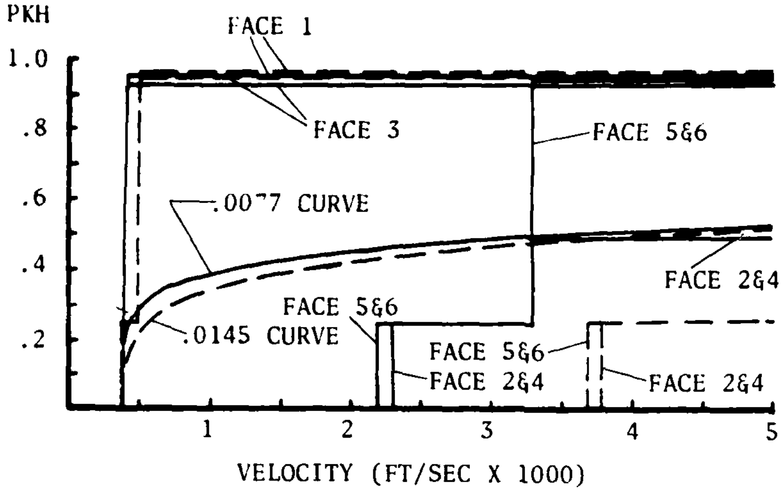


Fig. 10(l) - 18.0 Grains

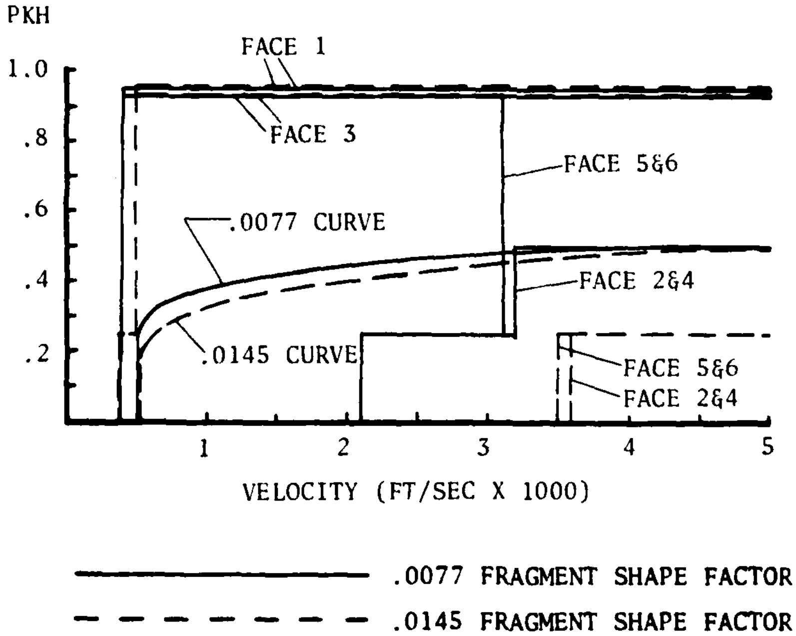


Figure 10. (Continued)

Fig. 10(m) - 20.0 Grains

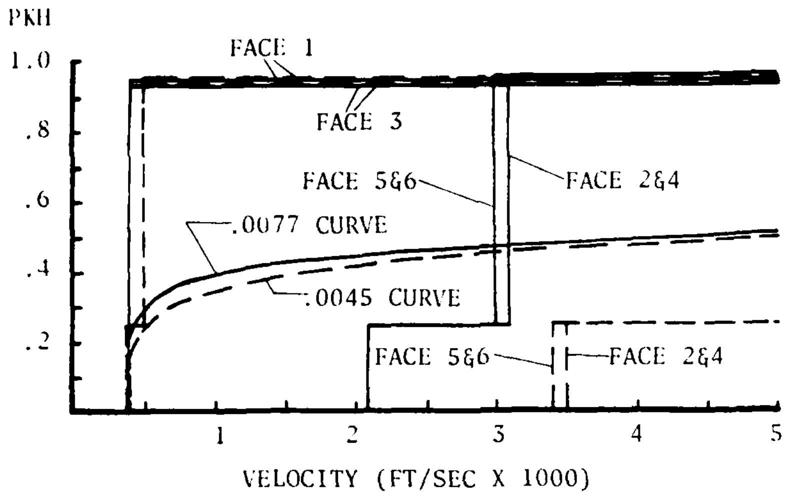


Fig. 10(n) - 40.0 Grains

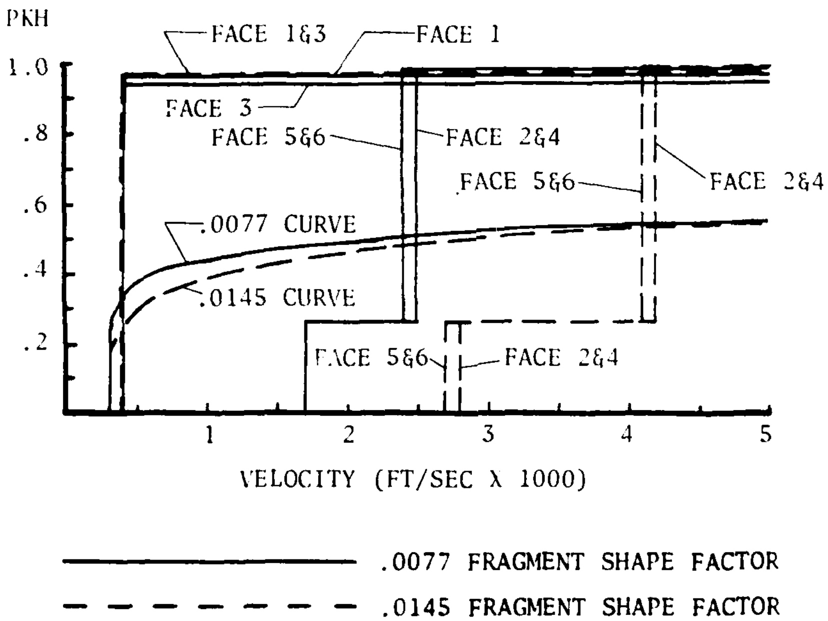


Figure 10. (Continued)

Fig. 10(o) - 60.0 Grains

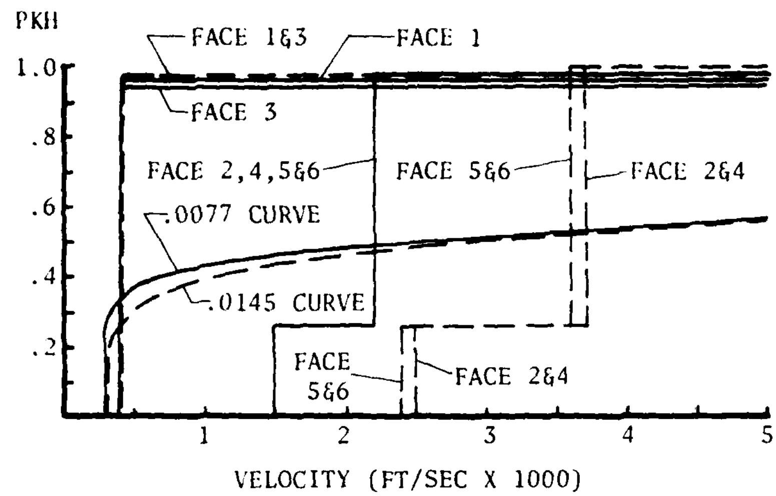


Fig. 10(p) - 80.0 Grains

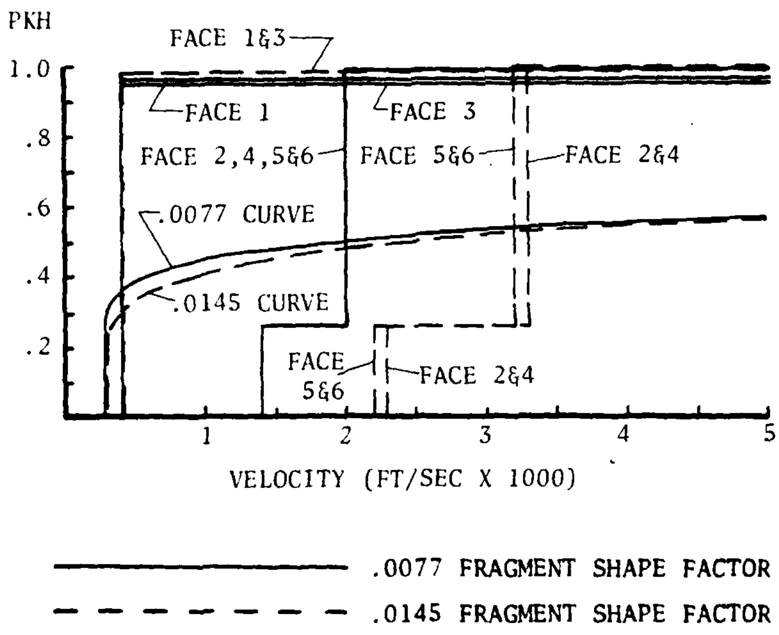


Figure 10. (Continued)

Figure 10e indicates that a 5.0-grain fragment with the smaller FSF (.0077) achieves a kill (at velocities greater than 3300 ft/sec) on Faces 2, 4, 5, and 6 whereas the larger FSF (.0145) does not. As seen in Table 1, although the kill hole requirement is small (0.09-inch diameter for one region on each face), the material is relatively thick (from 0.10 to 0.11 inch). Again, FSF has determined the vulnerability of the component faces. In this case, it is the more efficient penetrator, the fragment with a .0077 (spherical) FSF, which achieves the kill. Table 3 summarizes how FSF variations affect the vulnerability of each face of the component by indicating the minimum mass capable of achieving a kill on the component face with the optimum striking velocity (usually 5000 ft/sec). It is obvious that Face 1 is the one most vulnerable to fragments with either shape factor.

TABLE 3. Minimum Mass Capable of Penetrating (and Killing) the Sensitive Area of the M48A1 Tank Engine/Transmission Oil Cooler at Optimum Striking Velocity (Usually 5000Ft/Sec)

Fragment Shape Factor	Minimum Mass (Grains) to Kill Component					
	Face 1	Face 2	Face 3	Face 4	Face 5	Face 6
.0145	0.29[a]	6.69	3.19[b]	6.69	5.98	5.98
.0077	0.75[b]	2.11[c]	8.24[d]	2.11[c]	1.21	1.21

[a] Optimum fragment velocity = 800 ft/sec
[b] Optimum fragment velocity = 500 ft/sec
[c] Optimum fragment velocity = 4300 ft/sec
[d] Optimum fragment velocity = 400 ft/sec

Face 3 is the next most vulnerable face for the .0145 shape factor whereas Faces 5 and 6 are more vulnerable for the .0077 FSF. Greater vulnerability means the face can be killed by smaller fragment masses within the specified velocity range.

A summary of the PKH sensitivity of the M48A1 Tank Engine/Transmission Oil Cooler to shape factor for 3.0- and 20.0-grain fragments at 4000 ft/sec is provided in Tables 4 and 5. (This information has been extracted from Figure 9d and 9n). It will be noted in Table 4 that Face 1 is about equally vulnerable to 3.0-grain fragments of either shape factor but that Faces 2-6 are not vulnerable to a 3.0-grain fragment with .0145 shape factor. In Table 5 large variations in PKH, due to FSF changes, will be noted for Faces 2, 4, 5, and 6. The PKH's from the curve show only very little variation with changes in FSF.

It is evident that for many combinations of mass and velocity this component is very sensitive to FSF when it is analyzed by individual faces. When a distribution of fragment masses is specified, then the selection of a realistic shape factor is important in predicting the vulnerability of the component.

TABLE 4. Probability of Kill Given a Hit on the M48A1 Tank Engine/Transmission Oil Cooler by a 3.0-Grain Fragment at 4000 Ft/Sec

Fragment Shape Factor	Probability of Kill						
	Curve	Face 1	Face 2	Face 3	Face 4	Face 5	Face 6
.0145	.31	.94	.00	.00	.00	.00	.00
.0077	.34	.93	.08	.08	.08	.08	.08

TABLE 5. Probability of Kill Given a Hit on the M48A1 Tank Engine/Transmission Oil Cooler by a 20.0-Grain Fragment at 4000 Ft/Sec

Fragment Shape Factor	Probability of Kill						
	Curve	Face 1	Face 2	Face 3	Face 4	Face 5	Face 6
.0145	.49	.96	.25	.94	.25	.25	.25
.0077	.51	.95	.96	.93	.96	.96	.96

C. *Conclusions*

Although this was a limited study in which only one representative component was sampled, the following conclusions have been reached.

1. Variation in component PKH, due to variations in FSF, can be considerable when the vulnerability of a nonhomogeneous, nonsymmetrical type component is analyzed by individual faces. For example, in this analysis PKH's for an individual face varied from 0.0 to .92 for FSF variations of 88% (from .0077 to .0145). Accurate predictions of component vulnerability are dependent, in part, on the selection of striking FSF's which are representative of those which would be expected in the behind-armor debris.

2. There was very little variation in the selected component's PKH's when vulnerability was analyzed in the manner described, i.e., a single PKH (weighed average over all faces) was derived from a curve relating fragment MV/A (momentum/average area) to PKH. For example, the PKH's generated by the GENREG/MAXFIT curve varied from .42 to .36 for FSF variations of 88% (.0077 to .0145). Accurate selection of fragment shape factor does not significantly improve the accuracy of current component "average" PKH's (for this component) since greater inaccuracies are introduced by ignoring attack direction sensitivity and by utilizing the current GENREG/MAXFIT curve fitting routines.

3. FSF enters into the determination of component kill in two divergent ways. A fragment with large FSF (e.g., .0145 for random, steel artillery fragments) can produce large holes (to meet large kill hole requirements); however, they are not efficient at penetrating barriers. A fragment with the same mass but a smaller FSF (e.g., .0077 for spherical steel fragments) does not produce large holes, but is more efficient at penetrating barriers.

D. *Recommendations*

The following recommendations are offered:

1. The use of curve fitting routines and face-to-face averaging of PKH's in the present methodology should be eliminated since these mechanisms result in component PKH's which are insensitive to variations in FSF.

2. Investigations should commence to determine the feasibility of incorporating in the component vulnerability model and/or the point-burst model a mechanism for choosing realistic, representative FSF's to be used in the calculation of component PKH. If a point-burst model were modified to calculate component PKH only as needed (i.e., only when the component was hit by a computer-generated spall ray), then an FSF could be selected from some distribution of FSF's to provide the variations that might be observed in actual behind-armor debris.

VI. SENSITIVITY TO ENGINEERING JUDGMENTS

A. *Method*

In the PKHDOC Program the component kill criterion (minimum hole size in sensitive area required to kill the component), material thickness (thickness of material barriers between the striking fragment and the component's sensitive area), and sensitive area (that part of the total component which, if sufficiently damaged, will cause failure) are inputs provided by the component evaluator.

The kill criterion is used in the PKHDOC program to determine whether or not a particular fragment (with specific mass and shape factor) that has penetrated the sensitive area has killed the component. The impacting fragment has an average area, A_f, given by:

$$A_f = KM_s^{2/3} \tag{5}$$

where K is the fragment shape factor and M_s is the striking mass of the fragment. A_f is given by:

$$A_f = \left(\frac{d}{2}\right)^2 \pi \tag{6}$$

where d is the kill hole diameter specified by the component evaluator and π is the constant pi. Combining equations 5 and 6 and rearranging terms gives:

$$M_s = \left[\frac{\left(\frac{d}{2}\right)^2 \pi}{K} \right]^{\frac{3}{2}} \tag{7}$$

and we see that as the kill hole diameter, d, increases, the fragment striking mass, M_s, increases. In Table 6 an example is given of variations in fragment area, A_f, and striking mass, M_s, due to changes in kill hole diameter.

TABLE 6. Fragment Striking Mass (M_s) Variations Due to Changes in Kill Hole Diameter (d)

Hole Diameter d (inches)	Area of Hole with Diameter d A_f (inches^2)	Mass Required to make Hole with Area A_f M_s (grains)
0.25	0.05	6.2
0.50	0.20	49.8
0.75	0.44	168.2

(Note: FSF = .0145)

The material thickness of the component is used in the PKHDOC program as an input to the THOR penetration equations to compute residual mass, M_r, and residual velocity, V_r, of the fragment. The equations* for M_r and V_r are:

$$M_r = M_s - 10^{a_1} \left(tK\right)^{a_2} M_s^{\left(a_3 + \frac{2a_2}{3}\right)} \operatorname{Sec}\theta^{a_4} V_s^{a_5} \tag{8}$$

$$V_r = V_s - 10^{b_1} \left(tK\right)^{b_2} M_s^{\left(b_3 + \frac{2b_2}{3}\right)} \operatorname{Sec}\theta^{b_4} V_s^{b_5} \tag{9}$$

* Note: Equations 8 and 9 are identical to equations 3 and 4 and are restated here for convenience.

where:

M_r	=	residual mass (grains)
M_s	=	striking mass (grains)
a_1-a_5,b_1-b_5	=	THOR constants (based on material type)
t	=	barrier thickness (inches)
V_s	=	fragment striking velocity (ft/sec)
V_r	=	fragment residual velocity (ft/sec)
K	=	fragment shape factor (inches^2/grains$^{2/3}$)
θ	=	striking obliquity angle (degrees)

Equations 8 and 9 show that for a_2 and b_2 positive, (as they typically are), as the material thickness, t, increases, the residual mass, M_r, and residual velocity, V_r, decrease.

The sensitive area is used in the PKHDOC program in computing the probability of killing the component given a hit. This probability is the ratio of the sensitive area, A_k, (which has been penetrated by a fragment with mass sufficient to meet the kill hole requirement) to the total presented area of the component, A_p. In its simplest form* the conditional kill probability is given by:

$$PKH = \frac{A_k}{A_p} \tag{10}$$

Since no probability is computed in the PKHDOC program until it has been determined that a sensitive area has been penetrated with a "killing mass," PKH is actually the probability of hitting a component sensitive area given that you have hit the component with a killing mass. A_p is the physical measurement of each of the six faces of a particular component (as projected on an enclosing box) and is independent of the damage mechanism being considered. However, the size of A_k depends upon the mass and velocity of the impacting fragment. For example, a fragment with a particular combination of mass and velocity may be capable of penetrating (and killing) some portion (A_{k1}) of the total sensitive area. Increasing the velocity could result in the fragment (same mass) now being able to penetrate (and kill) an additional sensitive area (A_{k2}) of the same component. Thus, for the increased velocity, the total sensitive area penetrated is the sum of A_{k1} and A_{k2} and the PKH has increased from $\frac{A_{k1}}{A_p}$ to $\frac{A_{k1}+A_{k2}}{A_p}$. The PKH will also increase if the component evaluator increases the inputs for the sensitive area (presented areas remaining constant).

In order to determine PKHDOC variations in PKH as a function of variations in kill hole requirement (hole diameter), material thickness, and sensitive area, the PKHDOC program was exercised on the M48A1 Tank Engine/Transmission Oil Cooler for velocities up to 5000 ft/sec and for the masses given in Table 2. The parameters of kill hole requirement, material thickness, and sensitive area were varied by ±50% and the average PKH (over all six faces) was computed. The PKH's for each face were also computed for

* For a more comprehensive discussion of the PKHDOC methodology, see Armament Systems, Inc., *Documentation of $P_{K/H}$ Computer Program*, Anaheim, CA, November 1974.

these variations in input. The calculated average PKH's, the PKH's from the curve fit routines (GENREG/MAXFIT combination), and calculated PKH's for individual component faces for the ±50% variations were compared.*

B. *Results*

1. *Variations in Kill Hole Requirement:* Table 1 shows that the required kill hole diameter for the M48A1 Tank Engine/Transmission Oil Cooler is either 0.09 or 0.20 inches for all faces. The effects of varying these kill hole requirements by (±50%) on the fragment's average area, A_f, and striking mass, M_s, are presented in Table 7 where equations 6 and 7 were used to compute A_f and M_s.

TABLE 7. Variations in Fragment Striking Mass (M_s) Due to Changes in Kill Hole Diameter (d) for the M48A1 Tank Engine/Transmission Oil Cooler

Hole Diameter d (inches)	Area of Hole with Diameter d A_f (inches^2)	Mass Required to make Hole with Area A_f M_s (grains)
0.045 (-50%)	0.0016	0.04
0.090 (Baseline)	0.0064	0.29
0.135 (+50%)	0.0143	0.98
0.100 (-50%)	0.0079	0.40
0.200 (Baseline)	0.0314	3.19
0.300 (+50%)	0.0707	10.76

(Note: FSF = .0145)

The effects of ±50% variations in the required minimum hole diameter on component PKH as a function of the striking velocity of the fragment for a given mass are compared in Figure 11. The "average" PKH (average over six faces) step functions (from tabulated data) for the baseline, 50% increase, and 50% decrease in required hole diameter are

* Although PKHDOC was exercised for all input fragment masses in Table 2, results will be provided for only those of 4.0, 10.0, 18.0, and 80.0 grains for the .0145 FSF.

Fig. 11(a) - 4.0 Grains

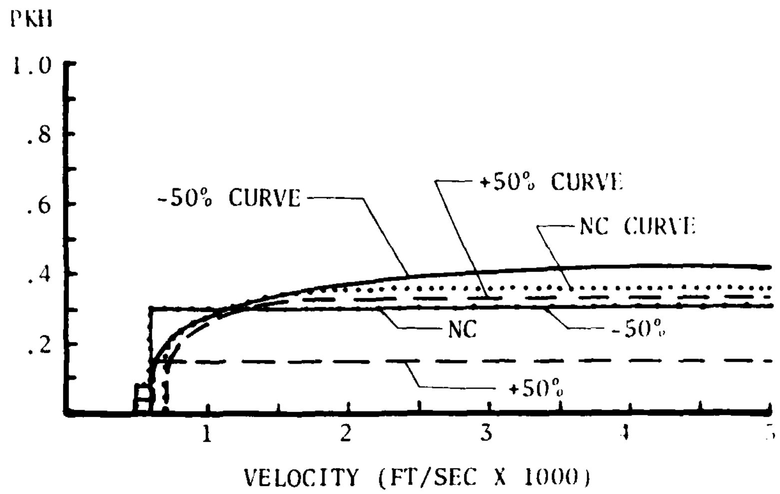
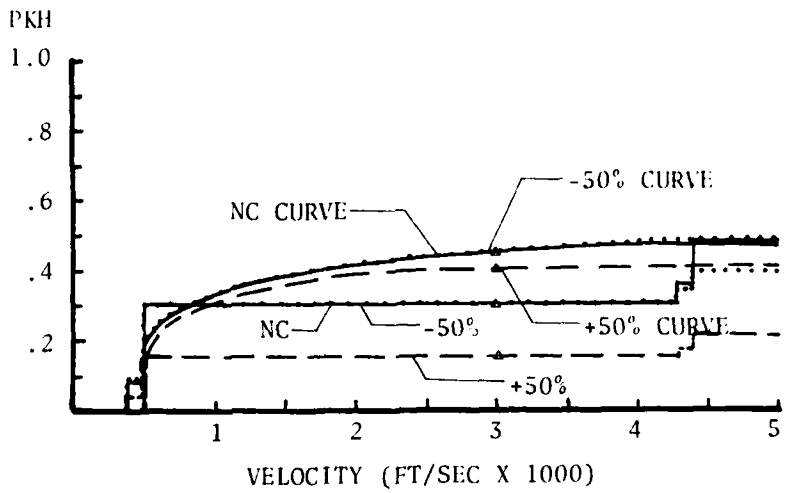


Fig. 11(b) - 10.0 Grains



△ INDICATES DATA POINT REFERENCED IN TEXT

——————————— -50% KILL HOLE REQUIREMENT VARIATION

— — — — — — — +50% KILL HOLE REQUIREMENT VARIATION

. . . . NO CHANGE (NC) OR BASELINE CASE

Figure 11. Probabilities of Kill (Given a Hit) as a Function of Fragment Velocity and Mass for ±50% Variations in Kill Hole Requirement for the M48A1 Tank Engine/Transmission Oil Cooler

Fig. 11(c) - 18.0 Grains

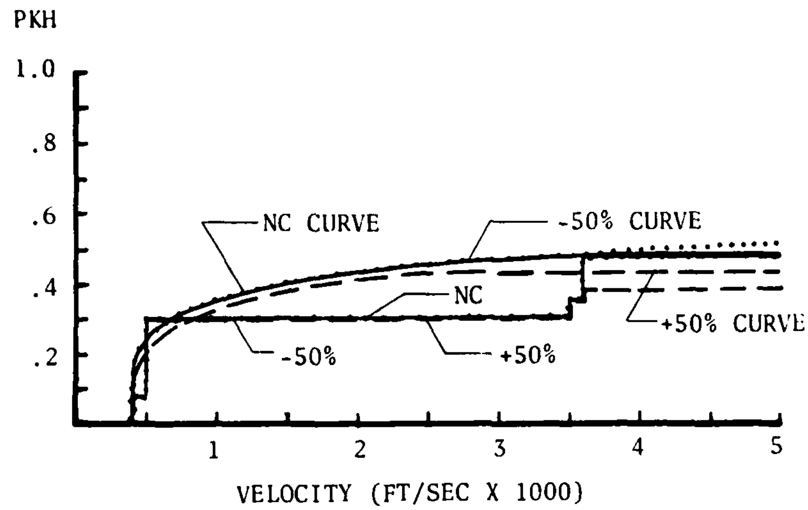
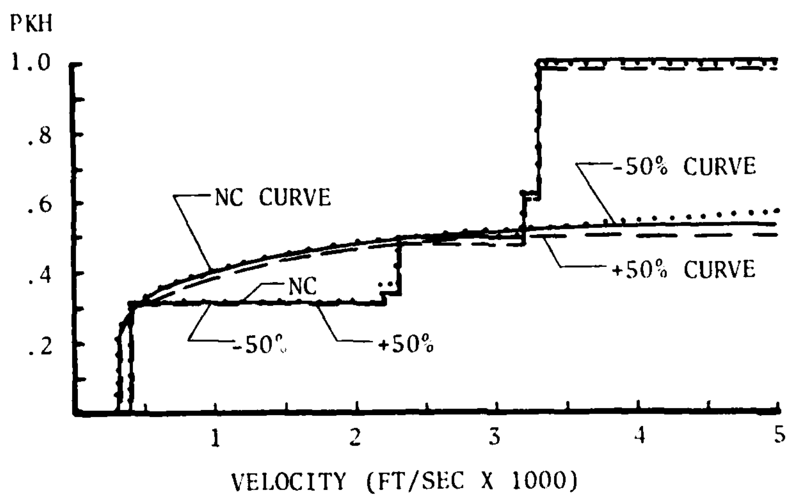


Fig. 11(d) - 80.0 Grains



—————— -50% MATERIAL THICKNESS VARIATION

— — — — — +50% MATERIAL THICKNESS VARIATION

· · · · · · · · · NO CHANGE (NC) OR BASELINE CASE

Figure 11. (Continued)

labeled, respectively, "NC," "+50%", and "-50%." The corresponding GENREG/MAXFIT combination curve fits evaluated for the specific masses indicated are labeled "NC CURVE," "+50% CURVE," and "−50% CURVE," respectively.

As seen in Figure 11b, a 10-grain fragment with velocity of 3000 ft/sec has a component PKH of .15 for +50% hole size, .30 for -50% hole size, and .30 for the baseline cases. This indicates that decreasing kill hole size for this component has no effect on PKH at this fragment mass and velocity. The GENREG/MAXFIT combination curve fits give a PKH of .40 for +50% hole size and .45 for -50% and baseline hole sizes. Figure 11(a-d) indicates that as the fragment mass increases, the ±50% variations in kill hole size produce decreasing variations in PKH step functions and PKH curve fits. This results from the fact that the kill holes required for this component are relatively small, and the larger fragment masses are able to produce holes sufficient to exceed even the increased requirements.

In Figure 12 variations in PKH step function are plotted for the individual faces of the selected component. The PKH's for individual faces are labeled with the appropriate face number. Figure 12a shows that for velocities above 600 ft/sec Face 1 has a PKH of .92 for the +50% variation and .95 for -50% variation. The baseline PKH (from Figure 2e) is .94 for this face. For Face 3, the PKH is 0.0 for the +50% case, and .95 for the -50% case. The baseline PKH for Face 3 (from Figure 2e) is .92. A review of Figure 12(a-d) indicates that increasing the size of the required kill hole by 50% makes Face 3 invulnerable to the smaller masses.

The minimum mass capable of killing a particular face of the component is presented in Table 8. As seen in this table, as the kill hole requirement is increased, the vulnerability of Faces 1 and 3 decreases, i.e., larger fragment masses are required to kill these faces. When Face 3 is compared with Faces 2, 4, 5, and 6, it can be seen that Face 3 is vulnerable to a smaller fragment mass for the baseline, but requires a larger fragment mass for the +50% kill hole requirement. Referring to Table 1, it will be noted that all faces except Face 3 have a sensitive area that requires only a 0.90-inch diameter hole to produce a kill. Table 7 indicates that the mass required to meet the kill hole requirement (0.0143 inch^2) for the +50% case is 0.98 grains for Faces 1, 2, 4, 5, and 6. From Table 8 it is apparent that Faces 2, 4, 5, and 6 require masses larger that 0.98 grains to produce a kill indicating that they are "penetration limited" (i.e., they require a larger mass to meet the penetration requirements due to the thickness of their barriers). However, Face 3 is "kill hole requirement limited" (i.e., it requires a larger mass to meet the hole requirement, 0.0707 inch^2).

Fig. 12(a) - 4.0 Grains

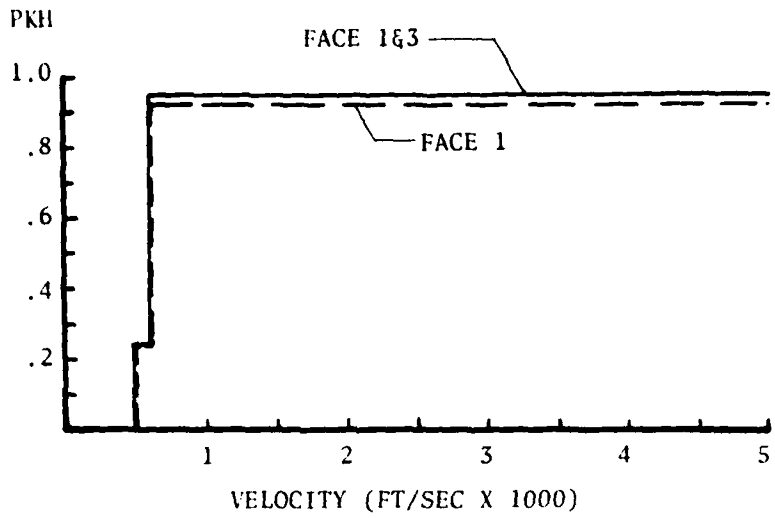
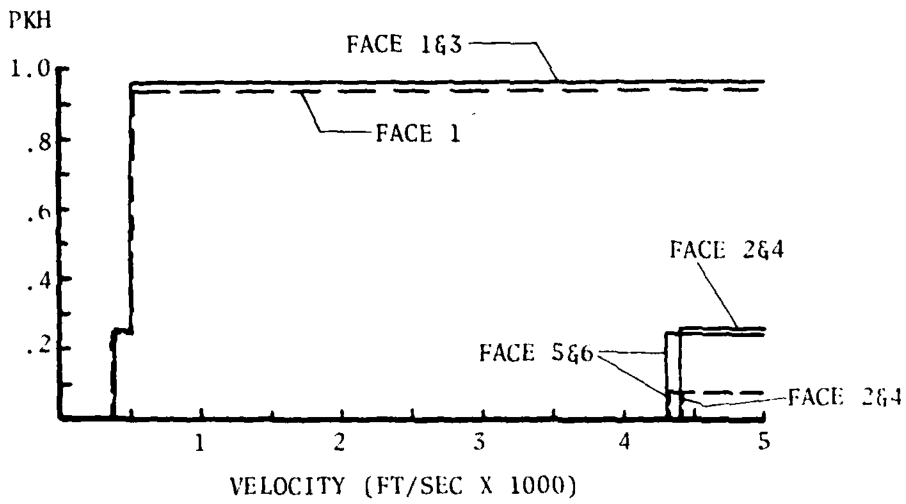


Fig. 12(b) - 10.0 Grains



———————— -50% SENSITIVE AREA VARIATION

— — — — — — — +50% SENSITIVE AREA VARIATION

Figure 12. Probabilities of Kill (Given a Hit) for Individual Faces of the M48A1 Tank Engine/Transmission Oil Cooler as a Function of Fragment Velocity and Mass for ±50% Variations in Kill Hole Requirement

Fig. 12(c) - 18.0 Grains

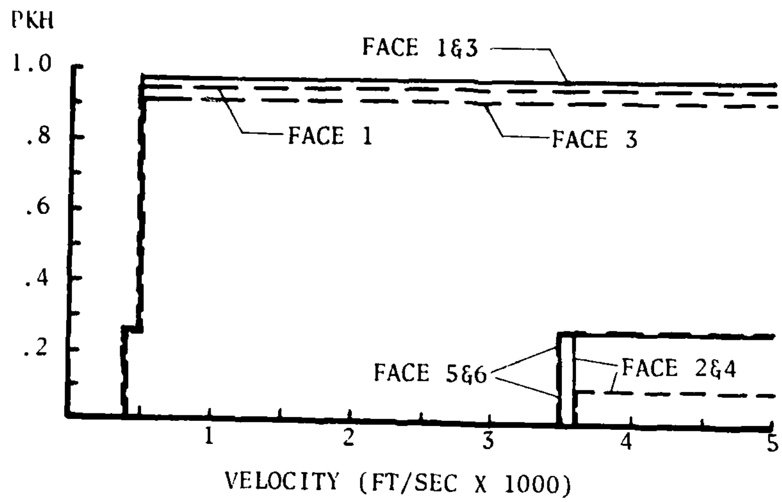
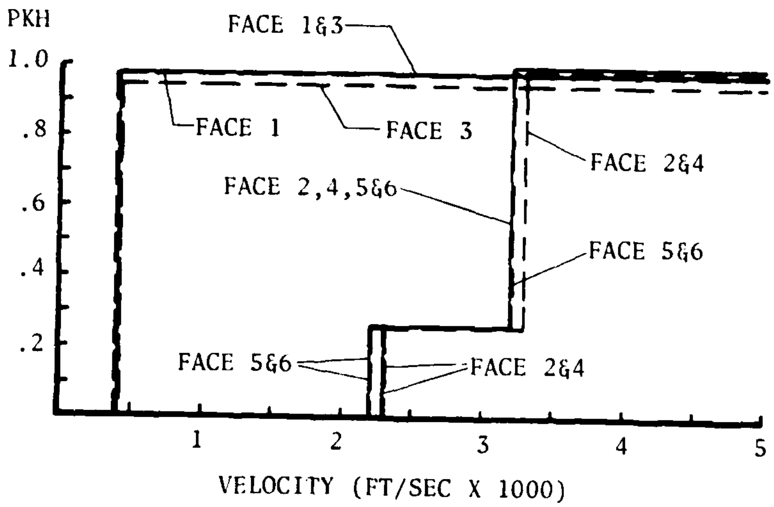


Fig. 12(d) - 80.0 Grains



—— -50% KILL HOLE REQUIREMENT VARIATION

– – – +50% KILL HOLE REQUIREMENT VARIATION

Figure 12. (Continued)

TABLE 8. Minimum Mass Capable of Penetrating (and Killing) the Sensitive Area of the M48A1 Tank Engine/Transmission Oil Cooler at the Optimum Striking Velocity (5000 ft/sec)

Kill Hole Diameter	Minimum Mass (Grains) Required to Kill Component					
	Face 1	Face 2	Face 3	Face 4	Face 5	Face 6
+50%	0.98[a]	6.69	10.76[b]	6.69	5.98	5.98
Baseline	0.29[c]	6.69	3.19[d]	6.69	5.98	5.98
-50%	0.04[e]	6.69	0.40[f]	6.69	5.98	5.98

(Note: FSF = .0145)

[a] Optimum fragment velocity = 600 ft/sec
[b] Optimum fragment velocity = 400 ft/sec
[c] Optimum fragment velocity = 800 ft/sec
[d] Optimum fragment velocity = 500 ft/sec
[e] Optimum fragment velocity = 2000 ft/sec
[f] Optimum fragment velocity = 700 ft/sec

2. *Variations in Material Thickness:* Table 1 shows the material thicknesses for the M48A1 Tank Engine/Transmission Oil Cooler to be 0.01 or 0.1 inch for all barriers. Varying 0.01 by ±50% results in barrier thicknesses from 0.005 to 0.0150 inch. Varying 0.1 by ±50% results in barrier thicknesses from 0.05 to 0.15 inch.

The effects of ±50% variations in material thicknesses on component PKH as a function of fragment striking velocity for a given mass are compared in Figure 13. The average PKH (average over six faces) step function (from tabulated data) for the baseline, 50% increase in material thickness, and 50% decrease in material thickness are labeled "NC," "+50%," and "-50%," respectively. The corresponding GENREG/MAXFIT combination curve fits evaluated for the specific masses indicated are labeled "NC CURVE," "+50% CURVE," and "-50% CURVE," respectively.

In Figure 13b it will be noted that a 10-grain fragment with velocity of 3000 ft/sec produces a step function PKH of .30 for the baseline thickness and +50% variation, and .47 for the -50% variation. The GENREG/MAXFIT combination curve fits give PKH's of .45 for the baseline, .37 for the +50%, and .58 for the -50% variations. At a velocity of 4000 ft/sec, the effect of decreasing the material thickness is greater (the PKH goes to .93). However, at velocities between 600 and 2300 ft/sec, ±50% variations in material thickness do not change the step function PKH's from the baseline of .30. Similar variations in PKH will be noted in Figure 13(a-d). In general, it will be noted that as the mass of the impacting fragment is increased, the range of velocities at which ±50% variations produce no change in step function PKH is decreased.

Fig. 13(a) - 4.0 Grains

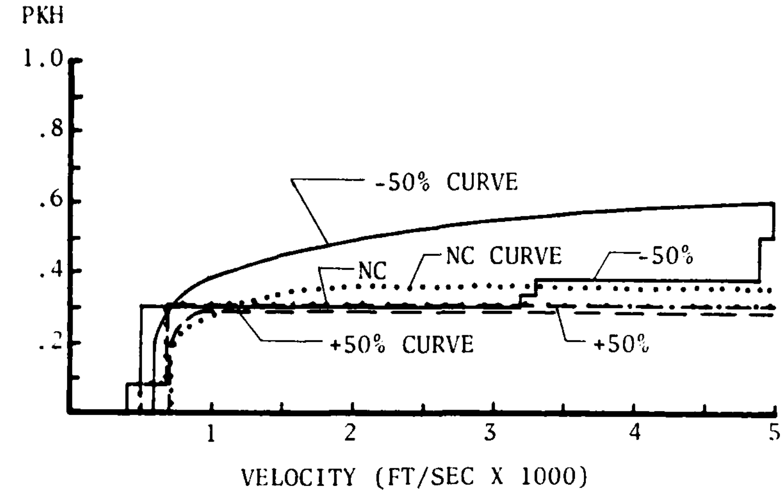
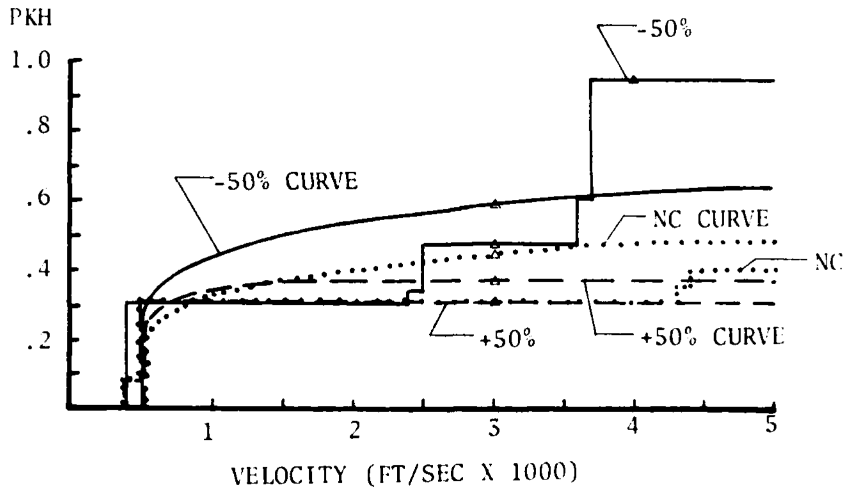


Fig. 13(b) - 10.0 Grains



△ INDICATES DATA POINT REFERENCED IN TEXT

———————— -50% MATERIAL THICKNESS VARIATION

— — — — — — — — +50% MATERIAL THICKNESS VARIATION

· · · · · · · · · · · · · · NO CHANGE (NC) OR BASELINE CASE

Figure 13. Probabilities of Kill (Given a Hit) as a Function of Fragment Velocity and Mass for ±50% Variations in Material Thickness for the M48A1 Tank Engine/Transmission Oil Cooler

Fig. 13(c) - 18.0 Grains

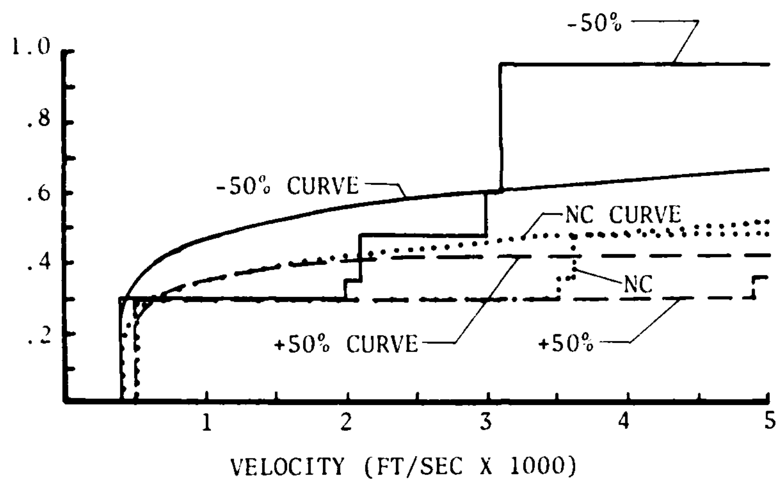
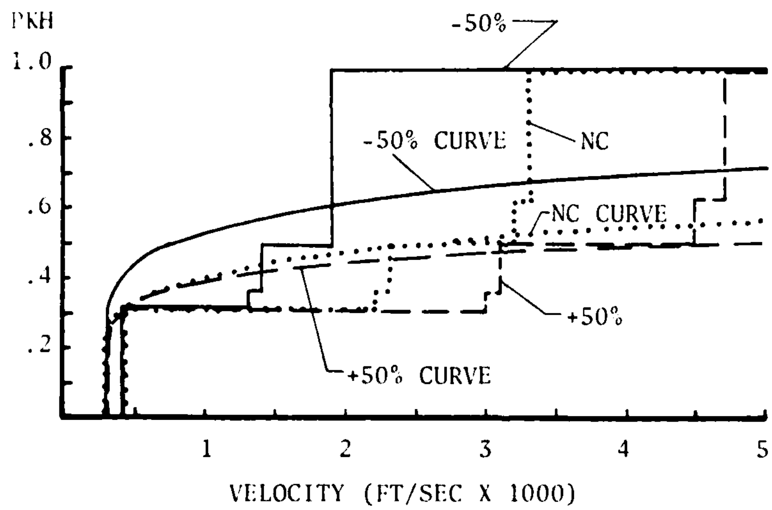


Fig. 13(d) - 80.0 Grains



———————— -50% SENSITIVE AREA VARIATION

— — — — — — +50% SENSITIVE AREA VARIATION

. . . . NO CHANGE (NC) OR BASELINE CASE

Figure 13. (Continued)

In Figure 14 variations in PKH step function are plotted for the individual faces for four masses. The PKH's for individual faces are labeled with the appropriate face number. Comparing Figures 14a and 2e shows that Faces 2, 4, 5, and 6 become vulnerable to 4.0-grain fragments when the material thickness is decreased by 50%. From comparing Figure 14b with Figure 2i, it can be seen that increasing the material thickness by 50% causes Faces 2, 4, 5, and 6 to become invulnerable to the 10-grain fragment. In general, increases in material thickness can cause certain faces to become invulnerable to specific fragment masses while decreases can cause the opposite effect. The summary in Table 9 shows the minimum mass capable of killing a particular face of the component for ±50% variations in material thickness as well as for the baseline. For Faces 2, 4, 5, and 6, increasing the material thickness decreases the component vulnerability (increases minimum mass required), and decreasing it increases the component vulnerability (decreases the minimum mass required). For Faces 1 and 3, ±50% variations in the material thickness do not change the minimum mass required to kill. This is because Faces 1 and 3 of this component are kill hole size limited and changing the material thicknesses, which are 0.01 inch, by ±50% has no effect on the minimum mass capable of killing these faces. Faces 2, 4, 5, and 6 are penetration limited; therefore, increasing material thickness increases the minimum mass required to kill these faces. The faces affected by variations in material thickness are not affected by variations in hole size and vice versa as seen by comparing Tables 8 and 9.

TABLE 9. Minimum Mass Capable of Penetrating (and Killing) the Sensitive Area of the M48A1 Tank Engine/Transmission Oil Cooler at the Optimum Striking Velocity (5000 ft/sec)

Material Thickness	Minimum Mass (Grains) Required to Kill Component					
	Face 1	Face 2	Face 3	Face 4	Face 5	Face 6
+50%	0.29[a]	18.53	3.19[b]	18.53	16.63	16.63
Baseline	0.29[c]	6.69	3.19[d]	6.69	5.98	5.98
-50%	0.29[d]	1.17	3.19[e]	1.17	1.04	1.04

(Note: FSF = .0145)

[a] Optimum fragment velocity = 1100 ft/sec
[b] Optimum fragment velocity = 400 ft/sec
[c] Optimum fragment velocity = 800 ft/sec
[d] Optimum fragment velocity = 500 ft/sec
[e] Optimum fragment velocity = 600 ft/sec

3. *Variations in Sensitive Area:* The sensitive areas of the M48A1 Tank Engine/Transmission Oil Cooler, shown in Table 1, were varied by ±50%. The resulting range, for use in computing component PKH's, is shown in Table 10.

Fig. 14(a) - 4.0 Grains

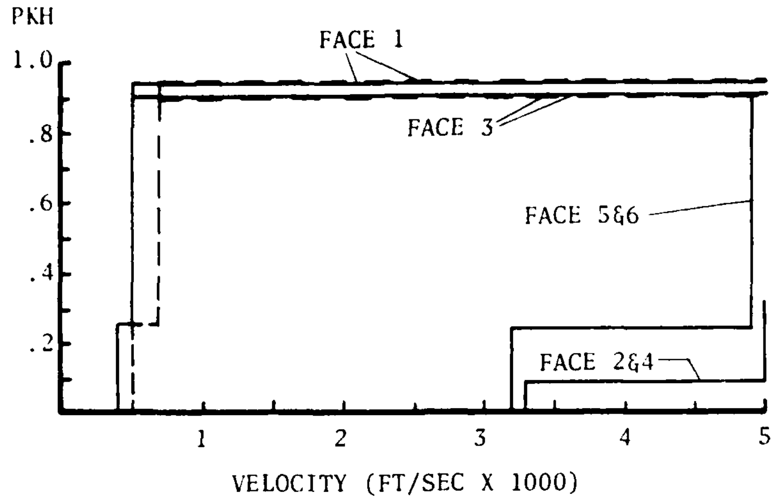
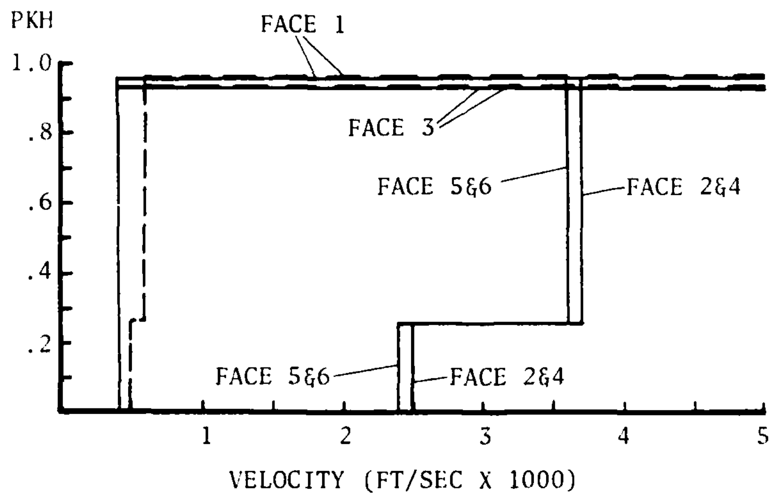


Fig. 14(b) - 10.0 Grains



——— -50% KILL HOLE REQUIREMENT VARIATION

– – – +50% KILL HOLE REQUIREMENT VARIATION

Figure 14. Probabilities of Kill (Given a Hit) for Individual Faces of the M48A1 Tank Engine/Transmission Oil Cooler as a Function of Fragment Velocity and Mass for ±50% Variations in Material Thickness

Fig. 14(c) 18.0 Grains

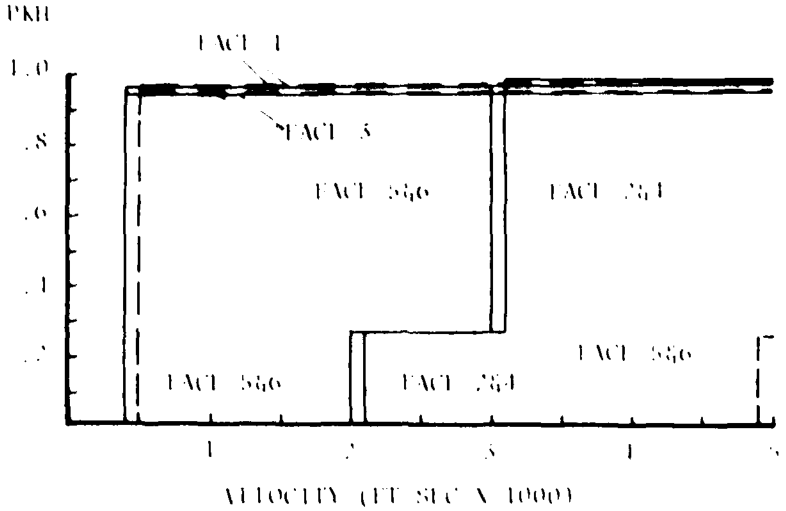
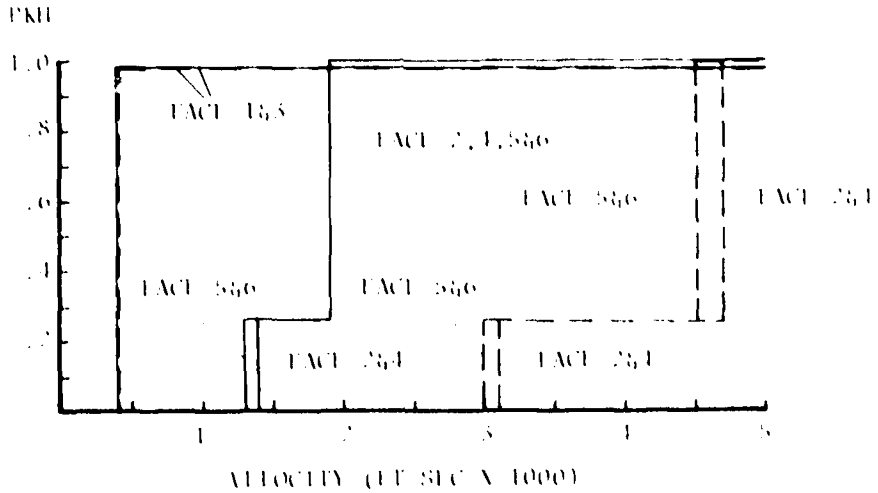


Fig. 14(d) 80.0 Grains



——————— -50% MATERIAL THICKNESS VARIATION

– – – – – – – +50% MATERIAL THICKNESS VARIATION

Figure 14. (Continued)

TABLE 10. Variations is Areas of the M48A1 Tank Engine/Transmission Oil Cooler

Face	Sensitive Area (SA) (sq inches)			Presented Area (PA) (sq inches)[a]
	-50%	Baseline	+50%	
1	137.2	247.4	265.7[b]	265.7
2	67.4	134.8	202.2	419.1
2	134.8	269.6	404.4	419.1
3	123.7	247.4	265.7[b]	265.7
4	67.4	134.8	202.2	419.1
4	134.8	269.6	404.4	419.1
5	23.3	46.6	69.9	150.0
5	46.6	93.2	139.8	150.0
6	23.3	46.6	69.9	150.0
6	46.6	93.2	139.8	150.0

[a] Total PA (at 0^{o} Obliquity) = 1669.6 sq inches
[b] Increase in sensitive area limited to the value of the presented area so that the SA/PA ratio is not greater than one.

A comparison of the effects of ±50% variations in sensitive areas on component PKH as a function of fragment striking velocity for a given mass is presented in Figure 15. The average PKH (average over six faces) step function for the baseline, 50% increase, and 50% decrease in sensitive area are labeled "NC," "+50%," and "-50%," respectively. The corresponding GENREG/MAXFIT combination curve fits evaluated for the specific masses indicated are labeled "NC CURVE," "+50% CURVE," and "-50%," respectively.

Figure 15b shows that a 10-grain fragment with a velocity of 3000 ft/sec produces a step function PKH of .30 for the baseline (NC), .32 for the +50%, and .15 for the -50% variations. The GENREG/MAXFIT combination curve fits give PKH's of .44 for the baseline, .46 for the +50%, and .24 for the -50% variations. In Figure 15a, c, and d similar

Fig. 15(a) - 4.0 Grains

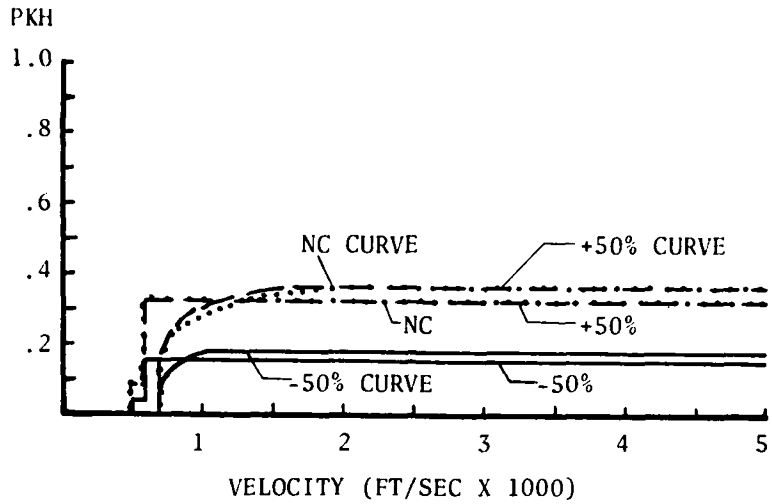
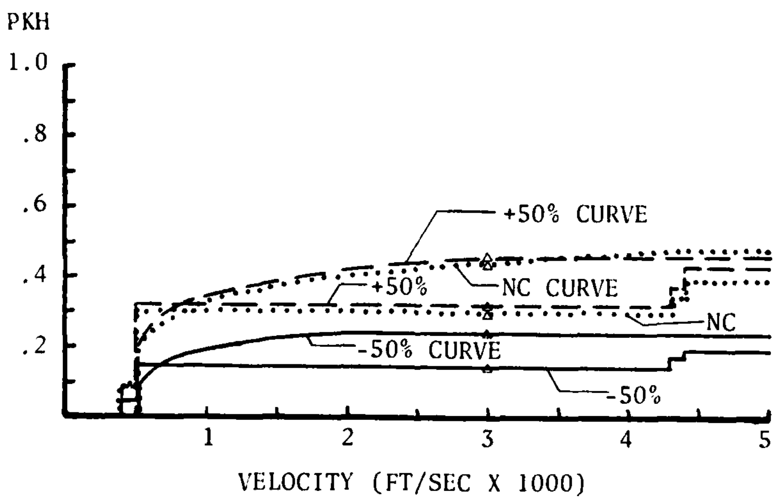


Fig. 15(b) - 10.0 Grains



△ INDICATES DATA POINT REFERENCED IN TEXT

——————— -50% SENSITIVE AREA VARIATION

— — — — — — — +50% SENSITIVE AREA VARIATION

. . . . NO CHANGE (NC) OR BASELINE CASE

Figure 15. Probabilities of Kill (Given a Hit) as a Function of Fragment Velocity and Mass for ±50% Variations in Sensitive Area of the M48A1 Tank Engine/Transmission Oil Cooler

Fig. 15(c) - 18.0 Grains

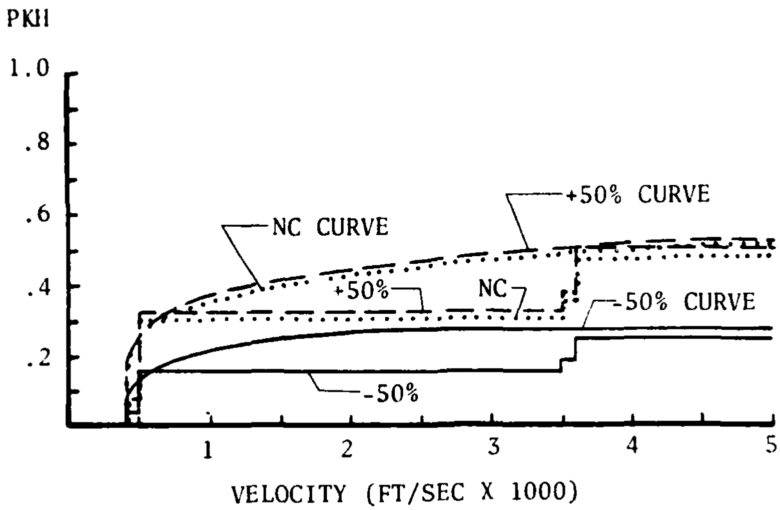
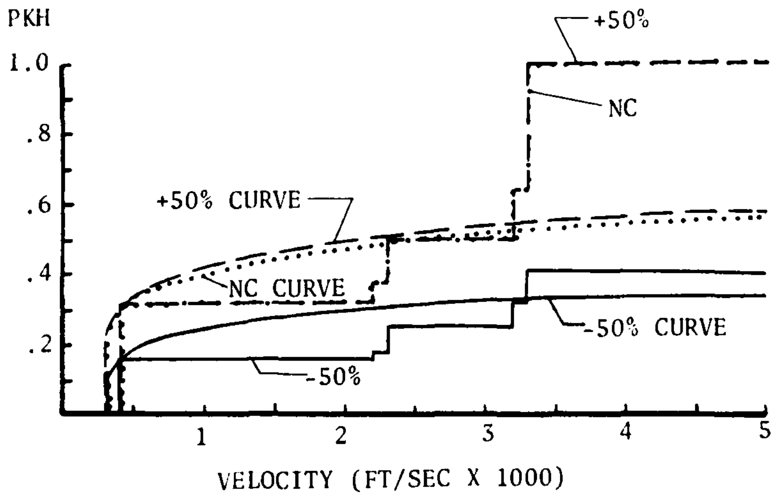


Fig. 15(d) - 80.0 Grains



———— -50% KILL HOLE REQUIREMENT VARIATION

— — — — +50% KILL HOLE REQUIREMENT VARIATION

· · · · · · · NO CHANGE (NC) OR BASELINE CASE

Figure 15. (Continued)

results are seen. In general, decreasing the sensitive area by 50% produces a significant decrease in component PKH. Increasing the sensitive area causes very little or no increase in PKH. Since the two most vulnerable faces (Faces 1 and 3) have high ratios of sensitive area to presented area (SA/PA), increasing the sensitive areas by 50% produces very little increase in PKH (by definition the ratio cannot be greater than one).

In Figure 16 variations in PKH step function are plotted for the individual faces of the component for four masses and labeled with the appropriate face number. The baseline case is not plotted here; however, there is very little difference between it and the +50% case for the reasons discussed in the previous paragraph. As would be expected, the individual faces of the component are readily affected by variations in sensitive area (Figure 16a-d). Decreases of 50% in sensitive area generally result in decreases in PKH of approximately 50% for this component.

4. *General:* In Figures 11, 13, and 15 the effects on component PKH due to variations in engineering judgments (i.e., kill hole requirement, material thickness, and sensitive area) were plotted as functions of fragment velocity for various fragment masses. As mentioned previously, the present method of analyzing component vulnerability utilizes some single PKH (weighted average overall component faces) which is derived from the GENREG/MAXFIT curve combination relating PKH to fragment momentum per average fragment presented area. The GENREG/MAXFIT curve combinations are indicated by the solid line labeled "−50% CURVE" and the dashed lines labeled "+50% CURVE." A comparison of the relative shift between the +50% and -50% shows that the ±50% variations in material thickness and sensitive area result in significant variations in the GENREG/MAXFIT curve PKH's, while there is very little variation in these for the ±50% variations in kill hole requirement. Comparing Figures 13 and 15 it appears that ±50% variations in material thickness produce variations in the GENREG/MAXFIT PKH's slightly greater than those produced by the ±50% variations in sensitive area.

In Figures 12, 13, and 15 the effects on the PKH's of each face of the component due to ±50% variations in the engineering judgments were plotted as functions of fragment velocity for various fragment masses. The PKH's for each face are labeled by the appropriate face number where dashed lines represent the +50% input variations and the solid lines represent the -50% input variations. The relative variation in PKH due to ±50% input variations are dependent upon the component geometry (face attacked), fragment mass, and fragment velocity. A summary of this is given in Table 11 for three specific combinations of these factors.

Fig. 16(a) - 4.0 Grains

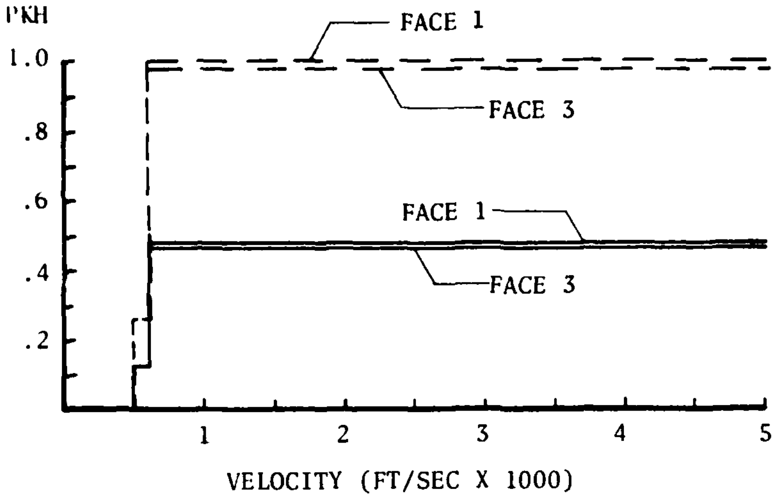


Fig. 16(b) - 10.0 Grains

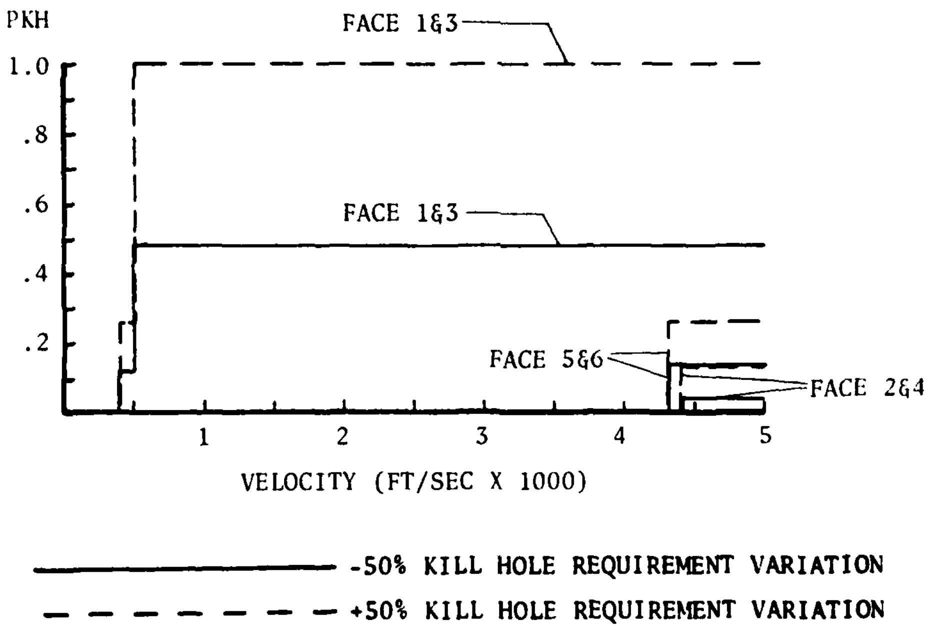


Figure 16. Probabilities of Kill (Given a Hit) for Individual Faces of the M48A1 Tank Engine/Transmission Oil Cooler as a Function of Fragment Velocity and Mass for ±50% Variations in Sensitive Area

Fig. 16(c) - 18.0 Grains

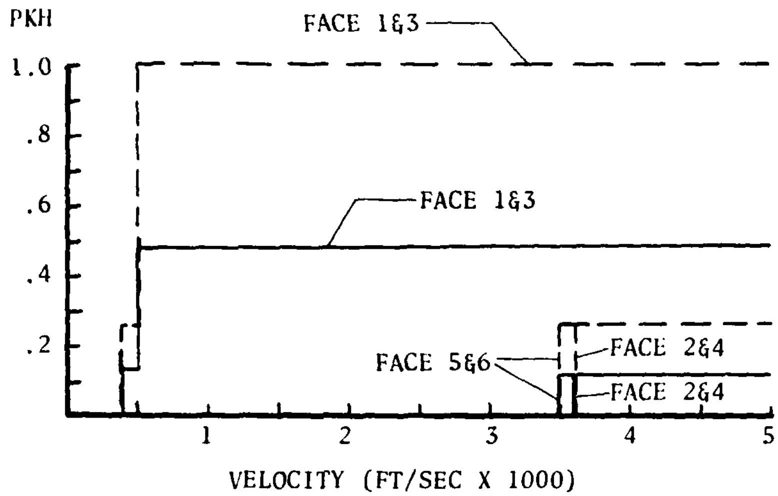
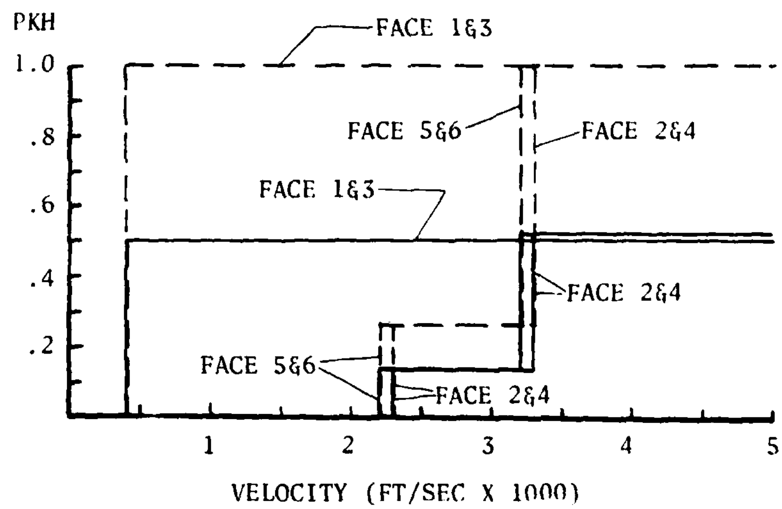


Fig. 16(d) - 80.0 Grains



——————— -50% MATERIAL THICKNESS VARIATION

— — — — — — — +50% MATERIAL THICKNESS VARIATION

Figure 16. (Continued)

TABLE 11. PKH Variations Due to ±50% Changes In Engineering Judgments for Three Specific Cases (M48A1 Tank Engine/Transmission Oil Cooler)

Engineering Judgment	Variation	Probability of Kill		
		CASE 1	CASE 2	CASE 3
		4.0 Grains at 1500 ft/sec Impacting Face 3	80.0 Grains at 3500 ft/sec Impacting Face 5	80.0 Grains at 5000 ft/sec Impacting Face 2
Hole Diameter	+50%	0.00	1.00	1.00
	-50%	.96	.99	1.00
Material Thickness	+50%	.92	.26	1.00
	-50%	.92	1.00	1.00
Sensitive Area	+50%	.98	1.00	1.00
	-50%	.46	.52	.50

(Note: FSF = .0145)

In case 1, the variation in kill hole requirement (diameter) produces the largest variation in PKH; in case 2, the variation in material thickness produces the largest variation in PKH; and in case 3, the variation in sensitive area produces the largest variation in PKH. Similar results can be seen by comparing Figures 12, 14, and 16.

C. *Conclusions*

Although this was a limited study in which only one "representative" component was sampled, the following conclusions have been reached:

1. *Variations in Kill Hole Requirement*

a. Variations in PKH due to ±50% variation in kill hole diameter can be significant when the vulnerability of a nonhomogeneous, nonsymmetrical type component is analyzed by individual faces. For example, varying the hole requirement by ±50% for one face of the M48A1 Tank Engine/Transmission Oil Cooler results in a +237%/-87% variation (from 10.8 to 0.4 grains) in the minimum fragment mass capable of killing this face, and results in variations in PKH values of from 0.0 to 0.94. In general, increasing the kill hole

requirement makes the component less vulnerable since larger masses are now required (assuming also that the larger masses can still penetrate the barriers). Decreasing the kill hole requirement generally has the opposite effect.

b. There is only modest variation in PKH when vulnerability is analyzed in the present PKHDOC manner; i.e., some single PKH (weighted average over all faces) is derived from a curve relating fragment MV/A (momentum/average area) to PKH for the entire specified mass range. For example, varying the hole requirement by ±50% for this component resulted in a maximum PKH variation of 36% (from .33 to .42), while the minimum fragment mass capable of killing the component (if it were attacked on its most vulnerable face) varied from 0.98 to 0.04 grains.

c. Accurate selection of the kill hole requirement does little to improve the accuracy of PKH (for this component) since greater inaccuracies are introduced by ignoring sensitivity to attack direction and by using the current GENREG/MAXFIT curve fit routines. For example, varying the kill hole requirement by ±50% caused the PKH's derived from the GENREG/MAXFIT curve fit to vary from .50 to .56, while the PKH's for the component's six individual faces actually ranged between .94 and 1.0.

2. *Variations in Material Thickness*

a. Variations in PKH due to ±50% variations in barrier material thicknesses can be significant when the vulnerability of a nonhomogeneous, nonsymmetrical type component is analyzed by individual faces. For example, varying the barrier thicknesses by ±50% for one face of the M48A1 Tank Engine/Transmission Oil Cooler results in a +177%/-82% variation (from 18.5 to 1.2 grains) in the minimum fragment mass capable of killing this face, and also results in PKH variations of from 0.0 to .98. In general, decreasing the thickness of the barrier material by 50% makes the component more vulnerable since the same fragment mass with a lower velocity may now penetrate the barrier, or a smaller fragment mass with the same velocity may now penetrate the barrier (assuming that the smaller mass is still large enough to meet the kill hole requirement). Increasing the thickness, generally, has the opposite effect.

b. Variations of ±50% in the material thickness produce less significant variations in PKH when vulnerability is analyzed in the present PKHDOC manner. Varying the material thickness by ±50% results in a maximum PKH variation of from .30 to .60 while the minimum fragment mass capable of killing this component was not affected and remained at .29 grains.

c. It is apparent that the inaccuracies introduced by ignoring sensitivity to attack direction and by using the current GENREG/MAXFIT curve fit routines are greater than those caused by the ±50% variations in thickness of barrier material. For example, variations in material thickness of ±50% caused the PKH's derived from the GENREG/MAXFIT curve fit PKH's to vary from .60 to .71, while the PKH's for the component's six individual faces actually ranged between .98 and 1.0.

3. *Variations in Sensitive Area*

a. Variations in PKH due to ±50% variations in sensitive areas can be significant when the vulnerability of a nonhomogeneous, nonsymmetrical type component is analyzed by individual faces. For example, varying the sensitive areas by ±50% for one face of the

M48A1 Tank Engine/Transmission Oil Cooler results in a maximum PKH variation of 108% (from .48 to 1.00). In general, decreasing the sensitive areas decreases the PKH (i.e., decreases the probability of hitting the sensitive area). Increasing the sensitive area generally has the opposite effect.

b. Varying the sensitive area has no effect on the fragment masses or velocities required to kill the component.

c. The effects of ±50% variations of sensitive area produce less significant variations in PKH when vulnerability is analyzed in the present PKHDOC manner. For example, varying the sensitive areas by ±50% for this component results in a maximum PKH variation of 77% (from .18 to .32).

d. It is apparent that the inaccuracies introduced by ignoring sensitivity to attack direction and by using the current GENREG/MAXFIT curve fit routines are greater than those caused by the ±50% variations in sensitive area. For example, variations in sensitive area of ±50% caused the PKH's derived from the GENREG/MAXFIT curve fit to vary from .30 to .49, while the PKH's for two of the component's six faces increased from .50 to 1.0 and the other four faces remained at 0.0.

4. *General*

a. For nonhomogeneous nonsymmetrical type components analyzed in the present PKHDOC manner, material thickness and sensitive area are about equally important, having a significant effect on PKH; whereas, kill hole requirement has very little effect. Therefore, in the present PKHDOC (GENREG/MAXFIT curve combination) methodology, accurate representation of material thickness and sensitive area are much more important than kill hole requirement.

b. In a face-to-face vulnerability analysis of a nonhomogeneous, nonsymmetrical type component, it is very difficult to conclude which engineering judgment has the greatest effect on PKH. All have significant impact on PKH; however, it was not possible to determine which was the most important since the relative effects of the variations produce variations in PKH which differ from case to case (i.e., vary due to component geometry, fragment velocity, and fragment mass). PKH variation appears to be a function of each individual combination of component/fragment inputs.

D. *Recommendations*

The following recommendations are offered:

1. For a PKH methodology based on face-to-face variations, great care should be given to the determination of kill hole requirements, material thicknesses, and sensitive areas as large variations in these parameters result in large variations in the PKH's of the individual faces of the component.

2. A sensitivity analysis of the point-burst model should be conducted in order to determine how much component variation in the PKH is allowable. These results could then be used to determine the necessary accuracy of kill hole requirement, material thickness, and sensitive areas.

VII. SUMMARY

A necessary input for a detailed point-burst methodology for analytically estimating the vulnerability of a target is a method of predicting the probability of rendering the components nonfunctional (PKH) given that they are subjected to some damage mechanism.

This study was conducted to investigate and quantify the sensitivity of component PKH's to attack direction and variations in several inputs to component vulnerability analysis, and to determine which of these inputs require detailed, accurate representation.

The Ballistic Research Laboratory's component vulnerability program (August 1978 version of PKHDOC) was utilized throughout this sensitivity study. The M48A1 Tank Engine/Transmission Oil Cooler was selected as the test component because it is representative of a typical nonhomogeneous, nonsymmetrical critical tank component.

Included in the study were:

1. A comparison of PKH's for individual faces of the test component with PKH's from the current "average PKH" methodology (weighted average over all faces derived from a curve relating component PKH to fragment momentum per average fragment presented area, MV/A).

2. A comparison of the effects on test component PKH's resulting from variations in fragment shape factor (from .0145 to .0077).

3. A comparison of the effects on test component PKH's resulting from ±50% variations in kill hole requirements, material thicknesses, and sensitive areas.

Variations in fragment shape factor and kill hole requirement had relatively little effect on test component PKH's computed by the current "MV/A curve fit" methodology. Variations in material thicknesses and sensitive areas produced significant variations in test component PKH's computed in this manner. However, the variations were most significant when PKH's thus computed were compared with those computed for individual faces of the test component. The inaccuracies introduced by the current "face averaging" and "curve fitting" routines far exceeded the inaccuracies introduced by variations in the other parameters tested.

It was concluded that significant improvement in component PKH accuracy would be realized by eliminating the present MV/A curve fitting routines and developing a PKH methodology for nonhomogeneous, nonsymmetrical type components that is sensitive to attack direction (face-to-face).

Fragment shape factor, component kill hole requirement, component material thickness, and sensitive area all had a significant effect on the face-to-face PKH's of the test component. Therefore, when a component vulnerability model sensitive to attack direction is implemented, the careful and accurate determination of these inputs will be necessary to insure the accuracy of the PKH's. The required accuracy of these inputs should be determined through sensitivity analyses of the point-burst (or component level) model.

Definitions

TERM	DEFINITION
AVE	PKH weighted average over all component faces
Average PKH	weighted average PKH over all six component faces
barriers	functionally inert surfaces between the outer surface of the component and its sensitive area
BRL	Ballistic Research Laboratory
component evaluator	a vulnerability analyst who is concerned with armored vehicle components
component face	one of the six two-dimensional surfaces on which one face of the three-dimensional component has been projected
CURVE	PKH plotted for a specific fragment mass from values taken from the GENREG/MAXFIT curve combination for the component
curve fit	GENREG/MAXFIT combination curve fit
curve fit PKH	component PKH for some given mass/velocity as determined from the GENREG/MAXFIT curve combination
FSF	fragment shape factor
GENREG	computer program regression curve fit (used in PKHDOC) which provides a curve showing component PKH as a function of fragment momentum per average fragment presented area (See also "PKH Step Function")

GENREG/MAXFIT curve combination	GENREG and MAXFIT regression curve fits utilized together to produce a single curve to predict component PKH as a function of fragment momentum per average fragment presented area (See also "PKH Step Function")
kill criteria	(See kill requirement)
kill hole requirement	(See kill requirement)
kill requirement	the minimum circular hole size in the component sensitive area required to kill the component
MAXFIT	computer program regression curve fit (used in PKHDOC) which provides the maximum component PKH attainable for any fragment mass. MAXFIT is used to limit the GENREG PKH values (See also "PKH Step Function")
point burst methodology	a method of analytically determining the vulnerability of armored vehicles in which the damage caused by behind-armor debris and the main penetrator are determined separately. (Each component is considered separately in this type of methodology.)
PKH	probability of kill give a hit (also $P_{K/H}$)
PKHDOC	computer program used at BRL to determine the vulnerability of armored vehicle components (specifically, an August 1978 version of PKHDOC.)
PKH step function	component PKH plotted, for a specific mass, from tabulated data (These step functions are developed by the PKHDOC program and provide the data from which the GENREG and MAXFIT curves are developed. See also "Tabulated Data.")

Presented area	total surface area of a three-dimensional component as projected on the six two-dimensional surfaces representing the component faces
sensitive area	that part of the presented area of a component which is susceptible to killing damage
tabulated date	the component PKH step functions generated by the PKHDOC program (These step functions provide component PKH, in discrete steps, as a function of fragment mass and velocity.)

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